Universidade de Aveiro2014

Departamento de Eletrónica, Telecomunicações e Informática

Rui Miguel Horta Coelho da Silva

Arquitetura WDM-PON com geração centralizada de multi-portadoras óticas

WDM-PON architecture with centralized generation of optical multi-carriers

Universidade de Aveiro2014

Departamento de Eletrónica, Telecomunicações e Informática

Rui Miguel Horta Coelho da Silva

Arquitetura WDM-PON com geração centralizada de multi-portadoras óticas

WDM-PON architecture with centralized generation of optical multi-carriers

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Eletrónica e Telecomunicações, realizada sob a orientação científica do Dr. Mário Lima (orientador) e do Dr. António Teixeira (coorientador), ambos do Departamento de Eletrónica, Telecomunicações e Informática e do Instituto de Telecomunicações - Aveiro.

Dedico este trabalho aos meus pais, amigos e restante família que sempre me apoiaram e que sem os quais não me teria sido possível completar este percurso académico.

O júri

Presidente

Prof. Doutor Paulo Miguel Nepomuceno Pereira Monteiro
Professor associado da Universidade de Aveiro

Vogais

Prof. Doutor Mário José Neves de Lima
Professor auxiliar da Universidade de Aveiro (Orientador)

Prof. Doutor Pedro Renato Tavares de Pinho
Professor Adjunto da Área Departamental de Engenharia de Eletrónica e Telecomunicações e de Computadores do Instituto Superior de Engenharia de Lisboa(Arguente Principal)

Agradecimentos

Gostaria de agradecer aos meus pais, restante família e também aos meu amigos por todo o apoio que me foi dado durante o decorrer do meu percurso académico e sem o qual não me teria sido possível concluir esta etapa da minha vida.

Gostaria também de agradecer a todos os alunos e professores do Departamento de Eletrónica e Telecomunicações da Universidade de Aveiro, que se cruzaram comigo durante o meu percurso académico e de que alguma forma me apoiaram, ajudaram e tornaram possível a conclusão deste percurso. Um especial agradecimento para os meus orientadores, Prof. Dr. Mário Lima e Prof. Dr. António Teixeira pela sua disponibilidade e pelo seu total apoio.

Palavras-chave

Redes de acesso, WDM-PON, geração de multi-portadoras ópticas, UDWDM-PON, MZM, pentes de frequências ópticas.

Resumo

O rápido crescimento do setor das telecomunicações e a crescente procura de largura de banda por parte dos utilizadores, levou à necessidade de desenvolvimento da arquitetura wavelength-division multiplexed passive optical network (WDM-PON), que permite aumentar a largura de banda da rede existente sem a necessidade de instalar nova fibra.

Uma técnica chave para a criação de redes WDM-PON de alta capacidade é a geração de multi-portadoras óticas. Esta técnica é o principal foco desta dissertação, que começa por olhar para a geração de multi-portadoras óticas de uma forma geral e de seguida vai encontrar a melhor forma para aplicar esta técnica a uma aplicação Ultra Dense WDM-PON (UDWDM-PON). Dois métodos distintos de gerar multi-portadoras foram testadas e foi concluído que o ‘single stage dual arm driven MZM’ é o método que mais benefícios apresenta para uma aplicação UDWDM-PON.

Keywords

Access Networks, WDM-PON, generation of optical multi-carriers, UDWDM-PON, MZM, optical frequency combs.

Abstract

The rapid growth of the telecommunications area and the increasing demand for bandwidth by users has led to the need of develop the Wavelength-division multiplexed passive optical network (WDM-PON) architecture, which can increase the bandwidth of the existing network without the necessity of installing new fiber .

A key technique for the high capacity WDM-PON networks is the generation of optical multi-carriers. This technique is the main focus point of this dissertation, which begins to look at the generation of optical multi-carriers in a general way and then will try to find the best way to apply this technique to an Ultra Dense WDM-PON (UDWDM-PON) application. Two distinct methods of generating optical multi-carriers were tested and it was concluded that the ‘single stage dual arm driven MZM’ is the one that offers more benefits to an UDWDM-PON application.

Table of Contents

List of figures

List of Tables

List of acronyms

CW	Continuous wave
DC	Direct Current
DS MOD	Dual stage modulator
EDFA	Erbium doped fiber amplifier
ECL	External cavity laser
FTTH	Fiber-to-the-home
IM	Intensity modulator
MZM	Mach-zehnder modulator
OCSA	Optical complex spectrum analyzer
OLT	Optical line terminal
ONU	Optical network units
OSNR	Optical signal-to-noise ratio
PC	Polarization controller
PON	Passive optical network
PM	Phase modulator
RF	Radio Frequency
RFS	Recirculating frequency shifting
RN	Remote node
SNR	Signal-to-noise ratio
SSB	Single-sideband
SS MZM	Single stage mach zehnder modulator
TDM	Time division multiplexing
UDWDM-PON	Ultra dense passive wavelength-division multiplexed optical network
WDM	Wavelength-division multiplexing
WDM-PON	Wavelength-division multiplexed passive optical network

1. Introduction

1.1. Context

The rapid growth of the telecommunications sector has led to a huge bandwidth demand from the costumers. As high-speed channels such as 100 Gb/s have become a reality and a necessity to meet the bandwidth requirement of optical networks nowadays, that deal with demanding technologies such as fiber-to-the-home (FTTH), the next step is to achieve and research 1 Tb/s and beyond transmission channels in order to prepare the future and support the always increasing demand of transmission capacity in data communications. Operators are being faced with the challenge of upgrading their networks and since laying new fiber is a very expensive and time wasting process, finding a way to use the existing fiber in a more efficient way has become fundamental to the development of telecommunications sector [1].

This upgrade in the existing networks can be accomplished in two ways, increasing the bit rate of the existing fiber via Time Division Multiplexing (TDM), or increasing the number wavelengths to be used on a fiber, Wavelength Division Multiplexing (WDM). But TDM, which consists in multiplexing a number of different signals in time by slicing time into smaller intervals so that the bits from multiple input sources can be carried on the link, is a limited technology that although meet the required bandwidth of today's networks, won't meet the likely requirements of the next generation of bandwidth-intense traffic. WDM is a technique that can combine multiple carriers at different wavelengths in a single fiber, this allows the increase of the fiber capacity by a factor that depends on the number of wavelengths used in that fiber [1,2].

A key technique for the Tb/s per-channel optical communications using a WDM-PON network is the centralized generation of optical multi-carriers. This technique allows the generation of an optical spectrum with equally spaced spectral lines (carriers) from a single continuous wave (CW) light source. There are multiple methods to obtain centralized generation of optical multi-carriers and each method will result in a frequency spectrum with different specifications, such as number of generated carriers, spacing between them and optical power of the spectrum. The different methods of generating optical multi-carriers and its specifications will be the main focus point of this dissertation [3].

WDM-PON is a fiber optic access network. Access networks are a mean to link the service provider to the customer's end of the network.

A PON, like shown on the figure 1.1, consists of point-to-multipoint connection between the Optical Line Terminal (OLT) and the Optical Network Units (ONUs). A single fiber connects the OLT to the Remote Node (RN) where optical splitters will divide the signal and take it to the different ONUs. The network between the OLT and the ONUs is passive which will result in no power consumption in this path [4].

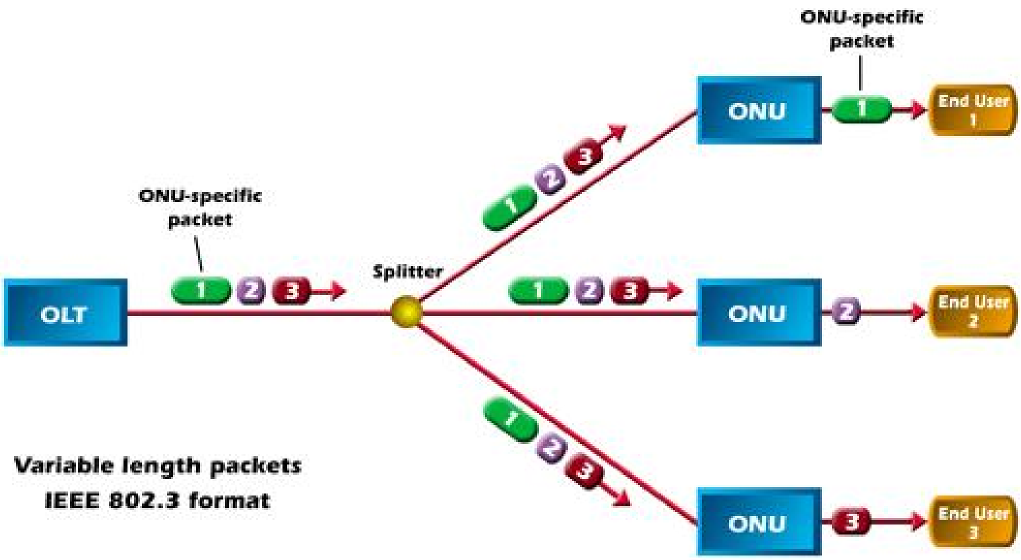

Figure 1.1-Downstream in a passive optical network[4].

1.2. Objectives

The main objectives of this dissertation are the following:

- Identify the existing methods for generation of optical multi-carriers;
- Identify the most suitable methods for generation of optical multi-carriers for a short range UDWDM-PON application;
- Simulation and validation of the best methods for generation of optical multi-carriers for a short range UDWDM-PON application;
- Experimentally test the simulated methods;
- Compare the chosen methods and find the one that best suits the desired application;

1.3. Structure

This dissertation is divided in the 5 following chapters:

- Introduction;
- Methods for generation of optical multi-carriers;
- Simulations;
- Experimental results;
- Conclusions;

In this first introductory chapter are presented the context, the objectives, the structure and the contributions.

In the second chapter are presented different methods for the generation of optical multi-carriers, as well as the selection of the ones that best suit a short range UDWDM-PON application.

The third chapter presents the simulations and validation of the selected setups.

In the fourth chapter are presented the experimental results of the selected setups, and in the fifth chapter conclusions about the setup that best suits the considered application are presented.

1.4. Contributions

The main contributions of this dissertation are:

- Description of several methods for generation of optical multi-carriers;
- Identification of the 'single stage dual arm driven MZM' and the 'dual stage intensity modulator and phase modulator' as the best methods for generation of optical multi-carriers for a short range UDWDM-PON application;
- Experimental validation of two setups to generate optical multi-carriers in the referred scenario;

2. Methods for generation of optical multi-carriers

The WDM architecture consists in using a spectrum with multiple spectral lines instead of just one spectral line. The best way to achieve multiples spectral lines is to use a centralized multi-carrier generation, because using a different laser for every spectral line requires too much hardware and it's a very expensive and unrealistic idea.

There are multiple methods to obtain centralized generation of flattened optical multi-carriers and each method will result in a frequency comb with different specifications.

The main schemes to generate these optical frequency combs are the dual stage intensity modulator and phase modulator, the single stage dual arm driven Mach-zehnder modulator (MZM), the cascaded phase modulators with intensity modulator and the single-sideband (SSB) modulator with recirculating frequency shifter (RFS) [5-10].

2.1. Dual stage intensity modulator and phase modulator

2.1.1. **Architecture**

This technique as seen on the figure 2.1 consists of a CW light source, a LiNbO3 mach-zehnder modulator (MZM) as intensity modulator (IM), a phase modulator (PM), a signal generator, a phase shifter, and amplifiers. The input light, a single wavelength, is modulated in the IM and PM by sinusoidal electrical signals generated in the signal generator. The voltages and phase of the electrical signals are adjusted by the amplifiers and the phase shifter, respectively. There can be an additional extra optical amplifier between the light source and the IM to provide more power to the optical signal [5,6].

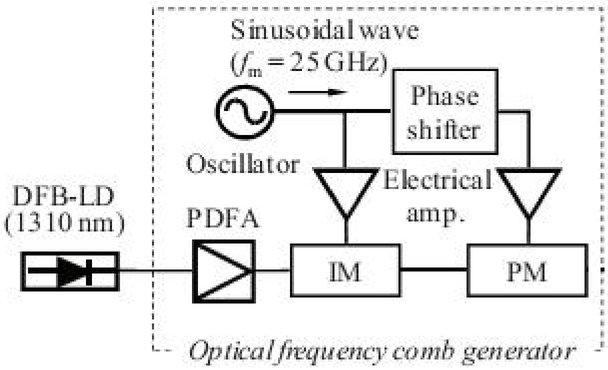

Figure 2.1-Configuration of the dual stage IM and PM[6].

2.1.2. **Advantages and Disadvantages**

With this technique it is possible to achieve a reasonable number of generated subcarriers, with some experiments already achieving over 30 subcarriers, and with good spectral flatness. This technique will however result in a signal with a limited optical signal noise ratio (OSNR) which will mean that the transmission distance will be quite limited [5,6].

2.2. Single stage dual arm driven MZM

2.2.1. **Architecture**

It is possible to create an optical frequency comb even when using a single-stage LiNbO3 MZM as seen on figure 2.2. In this technique an input CW light source is introduced into the modulator by a polarization controller to maximize modulation efficiency. Each arm of the MZM is modulated by a radio frequency (RF) signal. The RF sinusoidal signal is generated by a signal generator, divided into two different signals by a hybrid coupler and then these signals are shifted in frequency to obtain the appropriated flatness, amplified and fed to each of the modulator arms. The phase difference is set by a mechanically tunable delay line [7].

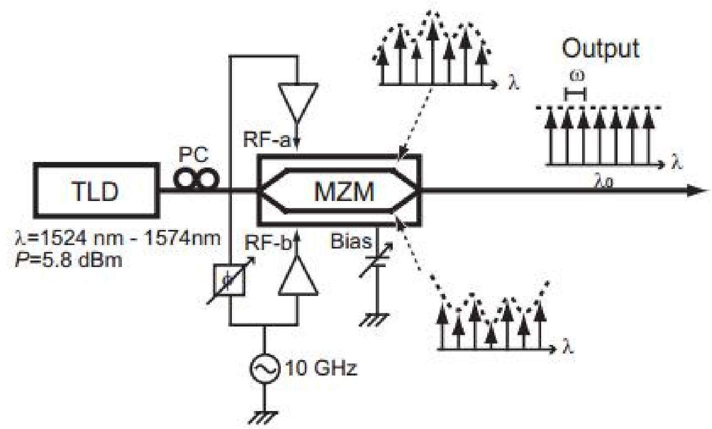

Figure 2.2-Configuration of the single stage dual arm driven LiNbO3 MZM[7].

2.2.2. **Advantages and Disadvantages**

With this scheme it is possible to generate an optical frequency comb with good spectral flatness and low noise. In this technique like in the dual stage optical frequency comb generator previously presented, it is possible to achieve a reasonable number of generated subcarriers, but this technique has proven to be a simpler and cheaper alternative [7].

2.3. Cascaded phase modulators with IM

2.3.1. **Architecture**

The cascaded phase modulators with IM is a technique similar to the dual stage MZM but where there will be multiple cascaded PM's instead of just one. In this technique, shown on figure 2.3, a CW lightwave from one narrow linewidth laser is modulated by a group of cascaded phase modulator driven by a radio frequency (RF) clock signal with a fixed frequency. After being modulated in the cascaded PM's, the signal will be modulated by an IM driven by the RF signal with a fixed frequency to generate flat optical subcarriers. In the scheme with only one PM, the number of subcarriers is limited due to the limited amplitude of the RF signal, so by cascading more PM's, it is possible to achieve a higher number of generated subcarriers. To achieve the maximum number of generated subcarriers, the phase relationship of the electrical signals must be optimal [8,9].

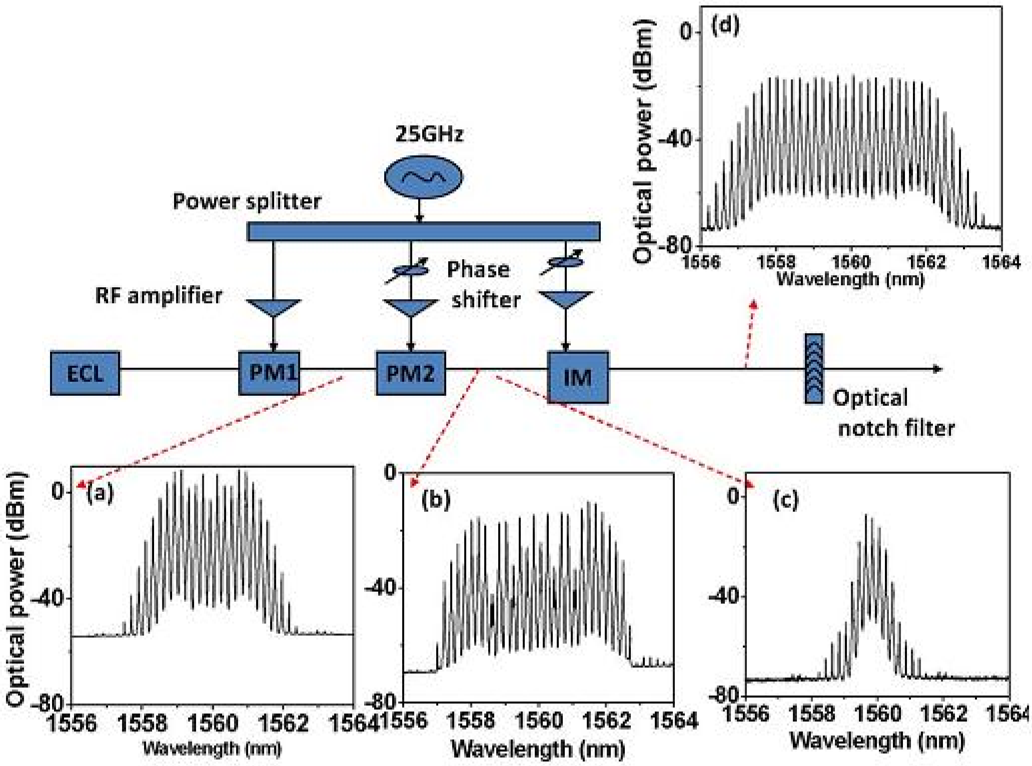

Figure 2.3-Cascaded phase modulators with IM. (a) subcarriers generated after the first PM, (B) maximum number of subcarriers generated after the two PM's, (c) minimum number of subcarriers generated after the two PM's, (d) flattened spectrum after the IM[8].

2.3.2. **Advantages and Disadvantages**

This technique allows the generation of multiple subcarriers with a high OSNR and good spectral flatness. Optical subcarriers generated by this technique are able to be transmitted by high speed systems over long distances. This technique will however, in order to get a flat power spectrum of subcarriers, result in a large insertion loss due to the use of an intensity modulator [8,9].

2.4. Single-sideband modulator with recirculating frequency shifting

2.4.1. **Architecture**

The single-sideband (SSB) modulator based on recirculating frequency shifting (RFS) is another popular technique to generate optical subcarriers. The configuration of this technique consists in a closed fiber loop, a3-dB coupler, a tunable optical filter, erbium doped fiber amplifiers (EDFAs) and a nested MZM. Using this method, it is possible to have the data modulation of the signal, before, after as shown on figure 2.5 or inside the RFS, as shown on figure 2.4.

To generate the subcarriers a single external cavity laser (ECL) source, acting as a seed is introduced in the RFS by the 3dB coupler, the 3dB is also used to close the recirculating loop, and output the generated subcarriers. The MZM will shift the original input carrier by a fixed frequency, making that at each new loop a frequency-locked new subcarrier will be generated. The number of generated subcarriers is controlled by the passband edge of the tunable optical filter. The EDFAs are used to compensate for the losses of the frequency shifter, the 3-dB coupler, and the optical filter [3,10,11].

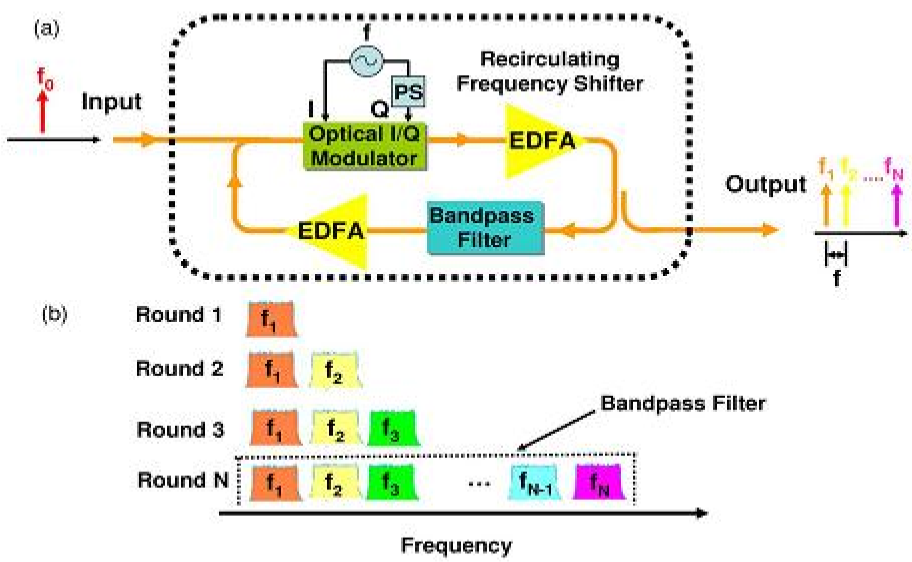

Figure 2.4-(a) Schematic of the RFS with data modulation inside the RFS, (b) operating principle of the RFS with a new carrier being generated at each loop[10].

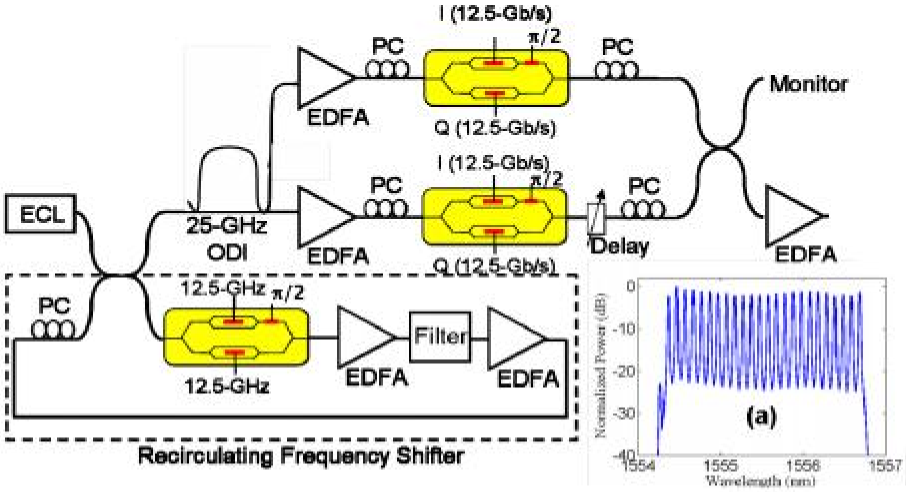

Figure 2.5-Schematic of the SSB based on RFS with data modulation being realized by two I/Q modulators after the RFS[11].

2.4.2. **Advantages and Disadvantages**

In this technique the number of generated subcarriers is strictly dependent on the number of times that the RFS loop is done. The OSNR of the generated subcarriers is not very high which won't allow for high speed signal transmissions over a long distance without Raman amplification [3,10,11].

2.5. Selecting the appropriate method for an UDWDM-PON application

Using the different techniques presented, different results will be achieved. Results may vary in terms of optical power, flatness of the spectrum, spectral linewidth, generated number of carriers and spacing between them. Different techniques should be applied according to the desired comb specifications or designed application.

In this dissertation, techniques for generating optical multi-carriers for a short range Ultra Dense WDM-PON (UDWDM-PON) application will be studied. The comb pretended should have between 12 and 20 narrow linewidth carriers for frequencies between 3GHz and 5 GHz, between 5 and 10 for the frequencies between 6GHz and 12.5GHz and good spectral flatness with a maximum ripple of 5dB.

From the schemes presented the ones who better fill the desired specifications with the least amount of hardware used are the dual stage IM and PM and the single stage dual arm driven MZM. These techniques were chosen because they allow the generation of the desired number of carriers within the spectral ripple limits established, low noise, high stability and narrow linewidth. All this is obtained with simple schemes that are easier and cheaper to achieve than the other schemes presented.

In order to test and validate each of these two methods, see the frequency spectra obtained and be able to compare them, both will be simulated using the program VPI[12] and then both of them will be experimentally tested in the laboratory.

3. Simulation

The single stage dual arm driven MZM (SS MZM) and the dual stage intensity modulator and phase modulator (DS MOD) were the two selected setups to generate an optical multi-carrier comb for an UDWDM-PON application but before experimentally testing these two setups, they must be validated as suitable methods for generation of optical multi-carriers and tested in order to better understand how each component of the setups will influence the resulting combs.

3.1. Single stage dual arm driven MZM

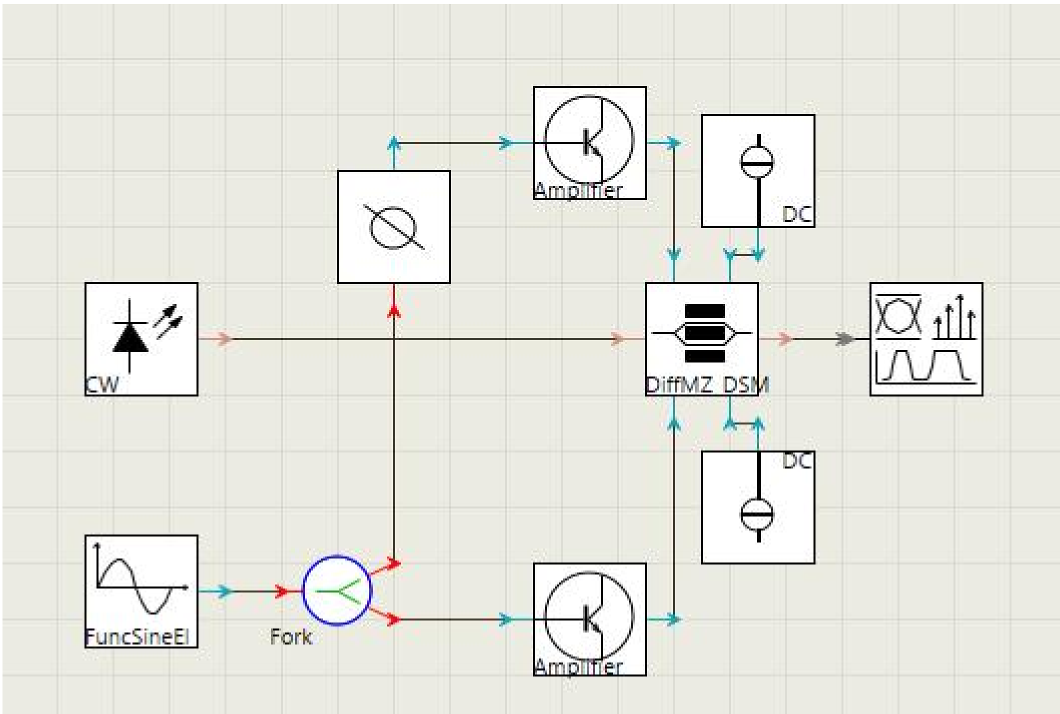

Figure 3.1-Single stage dual arm driven MZM setup simulated on VPI.

In the setup shown on the figure 3.1, it is possible to observe that there are two main branches, the optical branch and the RF branch. The optical branch is solely formed by a single CW laser and a dual arm driven MZM, while the RF branch is formed by a signal generator, the signal generated by this component will be split by a power splitter and these two resulting signals will be shifted in phase, amplified and fed to the RF inputs of the MZM. There are also two DC voltages that are fed to the DC inputs of the MZM and a signal analyzer to observe the spectrum generated by the MZM.

In order to optimize this setup, it is necessary to understand how changes in different parameters of the setup will affect the resulting spectrum. Some parameters are fixed and related to the hardware or the specifications of the comb pretended, and some are tunable and must be optimized in order to achieve a frequency comb that will fit the desired specifications. The spectrum can be affected in terms of number of carriers, spacing between the carriers, flatness of the comb and power of the carriers. The used parameters in each component of the setup will now be explained.

3.1.1. **Components**

- **Laser**

The continuous wave laser can be modeled in terms of emission frequency, average power and linewidth. The first parameter will define the wavelength on which the laser will emit and the central wavelength of the frequency spectrum comb after the signal is modulated, while the other two will define the power and the linewidth of the generated carrier.

- **Signal generator and amplifiers**

The signal generator can be modulated in terms of frequency and amplitude. The frequency set on the signal generator will be the only parameter that will influence the spacing between the carriers, being the spacing exactly equal to the value set on the generator. The power of the RF signal will influence the number of carriers generated, the higher the power that reach the MZM RF inputs after being amplified in the amplifiers, the higher will be the number of carriers generated.

- **Phase shifter**

The phase shifter will define the phase difference between both RF signals and this will affect the flatness of the comb.

- **MZM**

The values of VpiDC, VpiRF, insertion loss, extinction ratio and frequency response are set on the MZM model, all these values are not tunable and depend solely on the type of MZM used. The value of VpiDC will have influence in the flatness of the resulting comb, while VpiRF will have influence in the number of carriers generated, for the same RF signal, using a MZM with lower VpiRF will result in more carriers generated. The insertion loss will affect the comb in terms of power of the generated carriers, the extinction ratio will slightly influence the flatness of the comb and the frequency response will affect the bandwidth of the signal. The two DC voltages that are fed to the MZM DC inputs are tunable (from -15V to 15V) and will affect the comb in terms of flatness.

3.1.2. **Simulation results**

In order to prove and validate this setup as a suitable method for the generation of a flat comb of optical carriers, an optimization of some of the parameters used in the simulation must be done until a point is reached where the results will match the ones expected for this type of comb. The values that will be reached in this simulation will be used as the starting point for the values that will later be used in the experimental part of this dissertation.

The simulation was done using a laser wavelength of 1550nm (193.1THz) and for five different signal generator frequencies, 3.125GHz, 5GHz, 6.25GHz, 10GHz and 12.5GHz, as these are 5 common frequencies used in UDWDM-PON architectures. The RF signal at the signal generator output was set to 14.2dBm as this is the maximum power value available for the signal generator used experimentally, using higher power would result in a superior number of generated carriers. The values used for the MZM model were retrieved from the datasheet[13] of the MZM used experimentally (VpiDC=2V; VpiRF=2V; insertion loss=4dB; extinction ratio=25dB). For the simulation it was considered that the frequency response of the MZM was ideal, and consequently, for higher frequencies the carriers that are further away from the center wavelength will not present any loss, since the amplitude decay is expected to happen when using a real MZM with a non-ideal response.

The parameters that must be optimized for each frequency are the voltages that reach the RF inputs of the MZM through the amplifier gains, the DC voltages and the phase value in the phase shifter. All the other parameters will remain unchanged during the simulations because they are related to the specifications of the comb we want to obtain or the type of hardware used.

➢ Simulation tunings

Frequency(GHz)	3,125	5	6,25	10	12,5
Gain Amp 1(dB)	27	22,5	20,5	17,8	16
Gain Amp 2(dB)	26	21	19	16,2	14,5
VDC 1(V)	9	9	9,2	9,3	9,5
VDC 2(V)	4,5	4,5	4,4	4,3	4,2
Phase(degrees)	180	180	180	180	180

Table 3.1-Tunings used in the simulation for the SS MZM setup.

After optimizing the considered parameters, in order to achieve a flat frequency spectrum for the comb, it was found that the set of tunings presented in the table 3.1 resulted in a flattened spectrum comb for all the considered frequencies, thus validating the single stage dual arm driven MZM setup as a suitable method for the generation of optical multi-carriers.

➢ Results obtained

➢ 3.125GHz

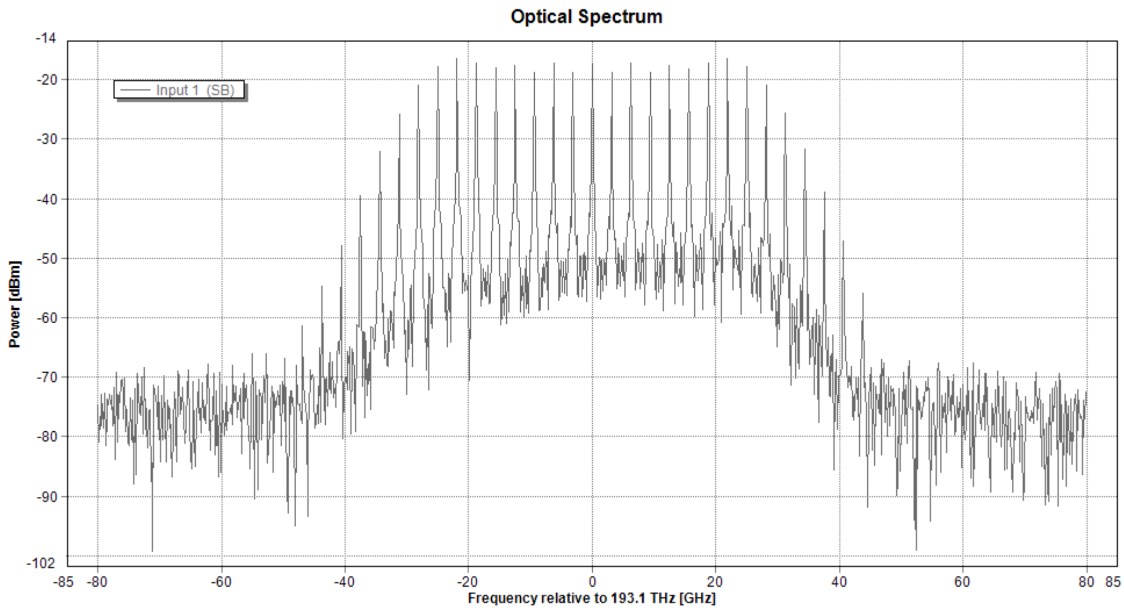

Figure 3.2-Results of the simulation of the SS MZM setup for 3.125GHz.

➢ 5GHz

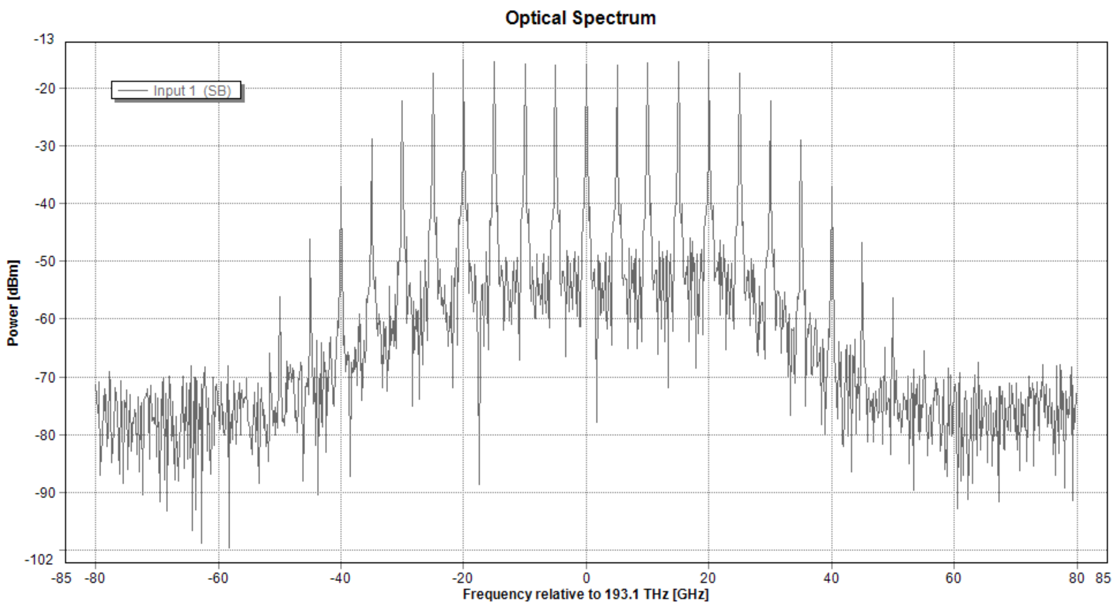

Figure 3.3-Results of the simulation of the SS MZM setup for 5GHz.

- 6.25GHz

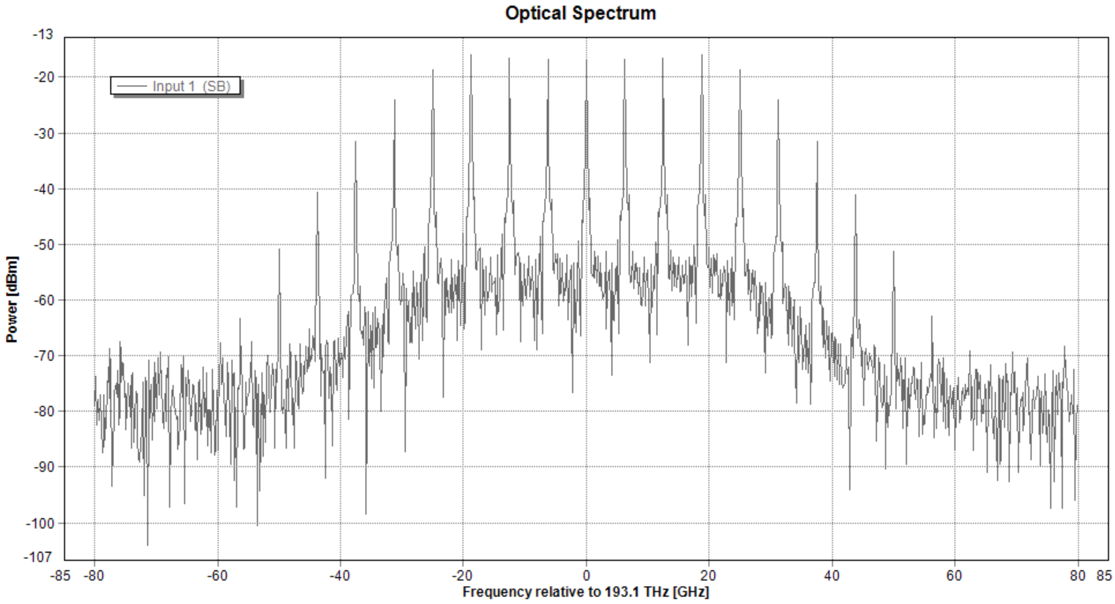

Figure 3.4-Results of the simulation of the SS MZM setup for 6.25GHz.

- 10GHz

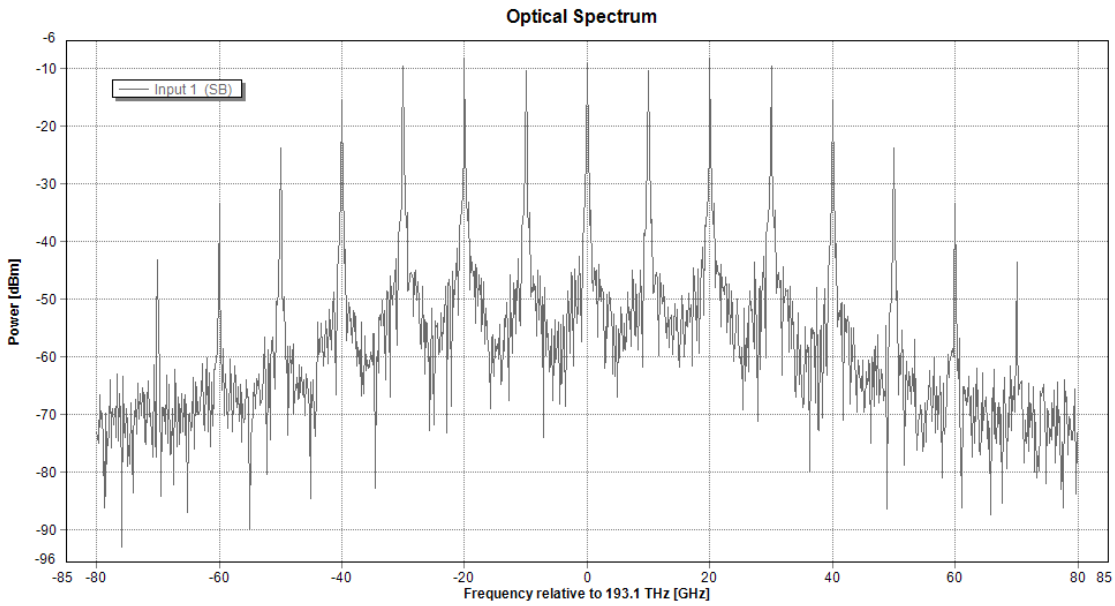

Figure 3.5-Results of the simulation of the SS MZM setup for 10GHz.

➢ 12.5GHz

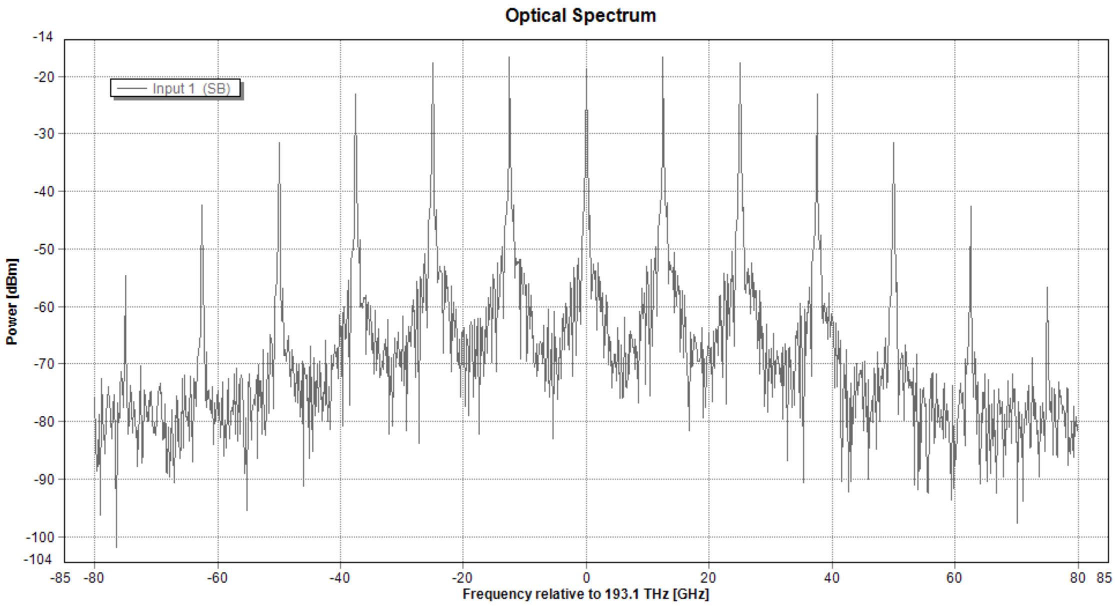

Figure 3.6-Results of the simulation of the SS MZM setup for 12.5GHz

Analyzing the simulation results obtained in the figures 3.2-3.6, it is possible to confirm that the spacing between carriers is equivalent to the frequencies set in the signal generator. It is also possible to observe that using the set of tunings presented in table 3.1 resulted in a flat spectrum with a maximum spectral ripple of 3dB for all the considered frequencies. For 3.125GHz 17 carriers were obtained, for 5GHz 11 carriers were obtained, for 6.25GHz 9 carriers were obtained, for 10GHz 7 carriers were obtained and for 12.5GHz 5 carriers were obtained. As the frequency response of the MZM model was ideal, if the gain of the RF signals remained as high in the simulations for the higher frequencies as it was in the simulation for 3.125GHz, the results would have presented the same number of channels for each frequency but with different spacing. As this won't happen in a real environment, the values of the RF signal gains were decreased for higher frequencies in order to better replicate what would happen with a MZM with a non-ideal frequency response.

3.2. Dual Stage intensity modulator and phase modulator

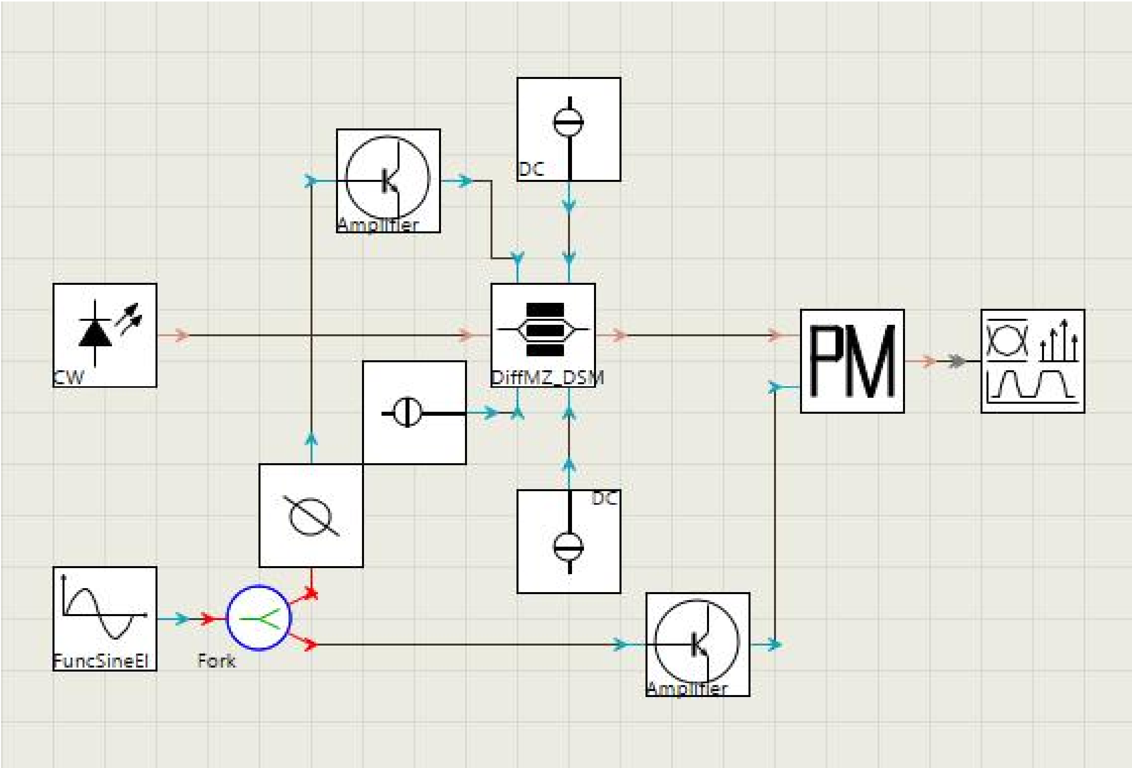

Figure 3.7-Dual stage IM and PM setup simulated on VPI.

The optical branch of the setup shown in the figure 3.7 is formed by a CW laser, a single arm driven MZM working as intensity modulator and a phase modulator. The RF branch is formed by a signal generator, where the signal generated will be split by a power splitter and these two resulting signals will be shifted in phase, amplified and one will be fed to one of the RF inputs of the IM and the other will be fed to the RF input of the PM. The other RF input of the IM will be connected to 0V. There are also two DC voltages that are fed to the DC inputs of the MZM and a signal analyzer to observe the spectrum generated after the PM.

The components used in this setup are similar to the ones used in the previous setup, with the exception that in this setup, a phase modulator is used. The PM has an associated phase deviation, PM's with different phase deviations will result in combs with different number of carriers and changed flatness. The spectrum can be affected in terms of number of carriers, spacing between the carriers, flatness of the comb and power of the carriers.

3.2.1. **Simulation results**

In order to prove and validate this setup as a suitable method for the generation of a flat comb of optical carriers and identically to what happened in the previous setup, optimization of some of the parameters is necessary to reach a point where the results will match the ones expected for this type of comb. The values obtained by this optimization will be used as the starting point for the values that will later be used in the experimental part of this thesis.

The simulation was done using a laser wavelength of 1550nm (193.1THz) and for the same five frequencies used in the previous setup, 3.125GHz, 5GHz, 6.25GHz, 10GHz and 12.5GHz. The RF signal and the MZM model working as IM will also be the same as the used in the previous setup. For the PM it was considered a phase deviation of 90 degrees.

The parameters that must be optimized for each frequency were the voltages that reach the RF inputs of the IM and PM through the amplifier gains, the DC voltages of the IM and the phase in the phase shifter. All the other parameters remained unchanged during the simulations because they are related to the specifications of the comb we want to obtain or the type of hardware used.

- **Simulation tunings**

Frequency(GHz)	3,125	5	6,25	10	12,5
Gain Amp 1(dB)	23	21	19	18	14
Gain Amp 2(dB)	21	19	15,5	14,5	11
VDC 1(V)	7	7	7	7	7
VDC 2(V)	7	7,2	7	7	7
Phase(degrees)	75	85	90	90	90

Table 3.2-Tunings used for the simulation of the DS MZM setup.

After optimizing the considered parameters in order to try to achieve a flat frequency spectrum, it was found that the set of tunings presented in the table 3.2 resulted in such a spectrum for all the considered frequencies, validating in this way the dual stage IM and PM setup as a suitable method for the generation of optical multi-carriers.

➢ Results obtained

➢ 3.125GHz

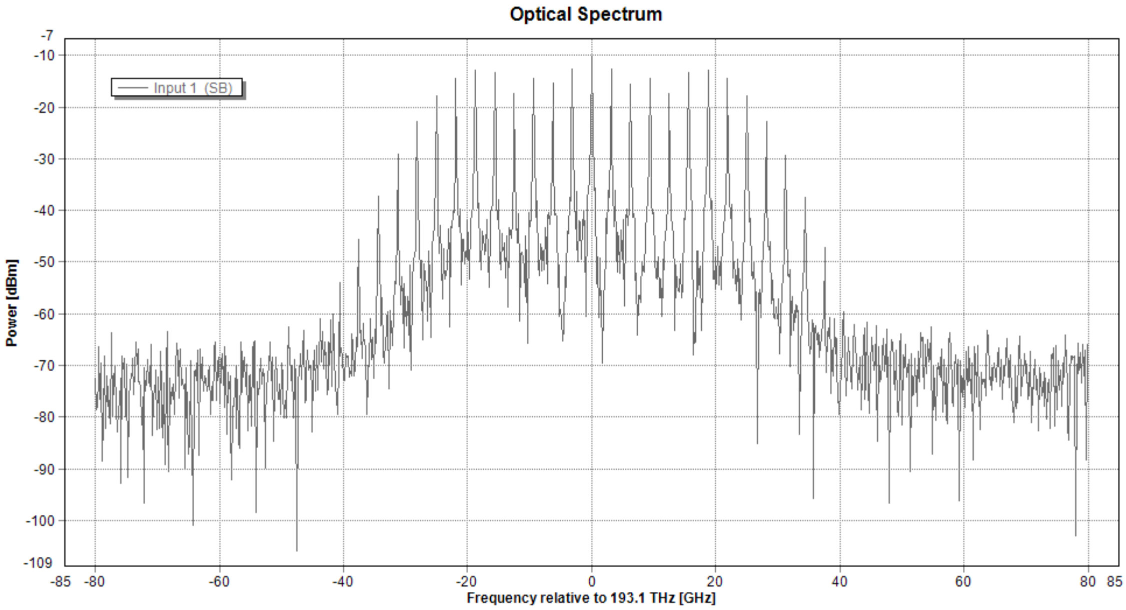

Figure 3.8-Results of the simulation of the DS MOD setup for 3.125GHz.

➢ 5GHz

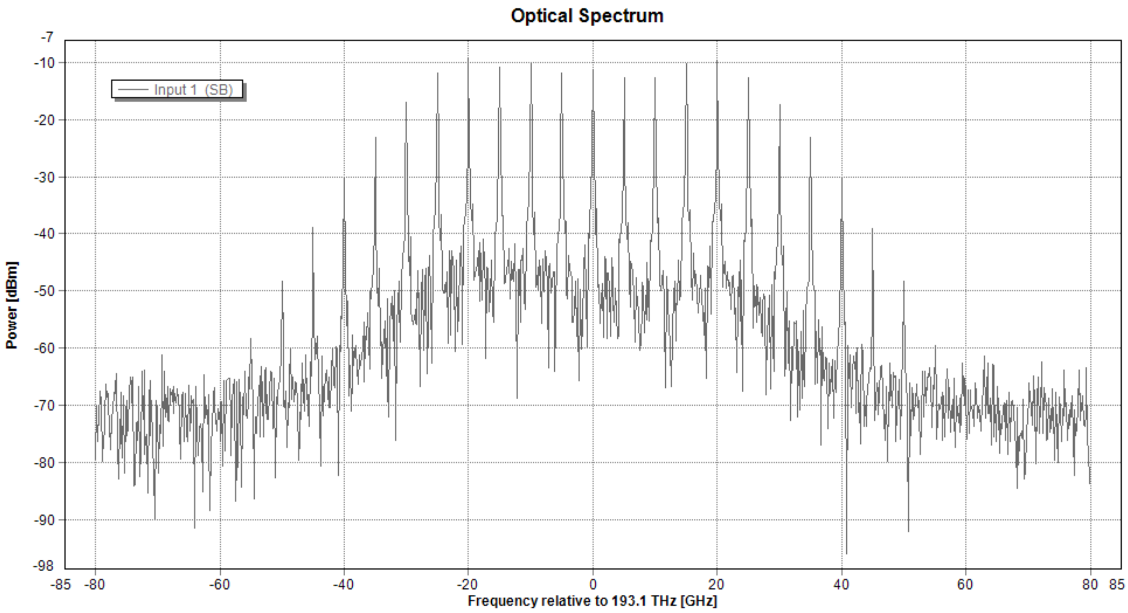

Figure 3.9-Results of the simulation of the DS MOD setup for 5GHz.

- 6.25GHz

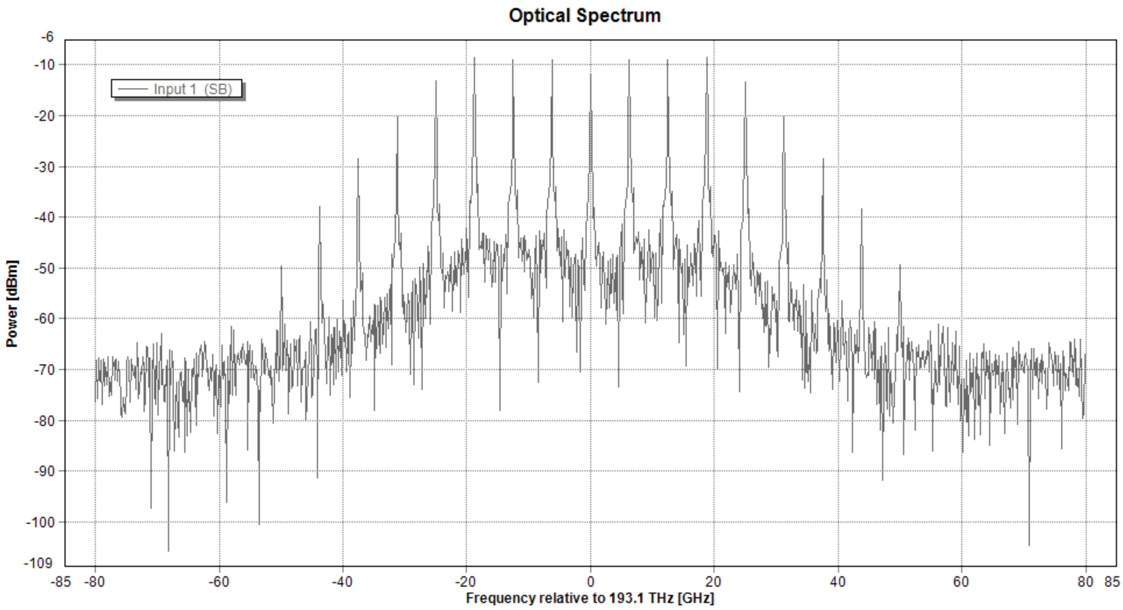

Figure 3.10-Results of the simulation of the DS MOD setup for 6.25GHz.

- 10GHz

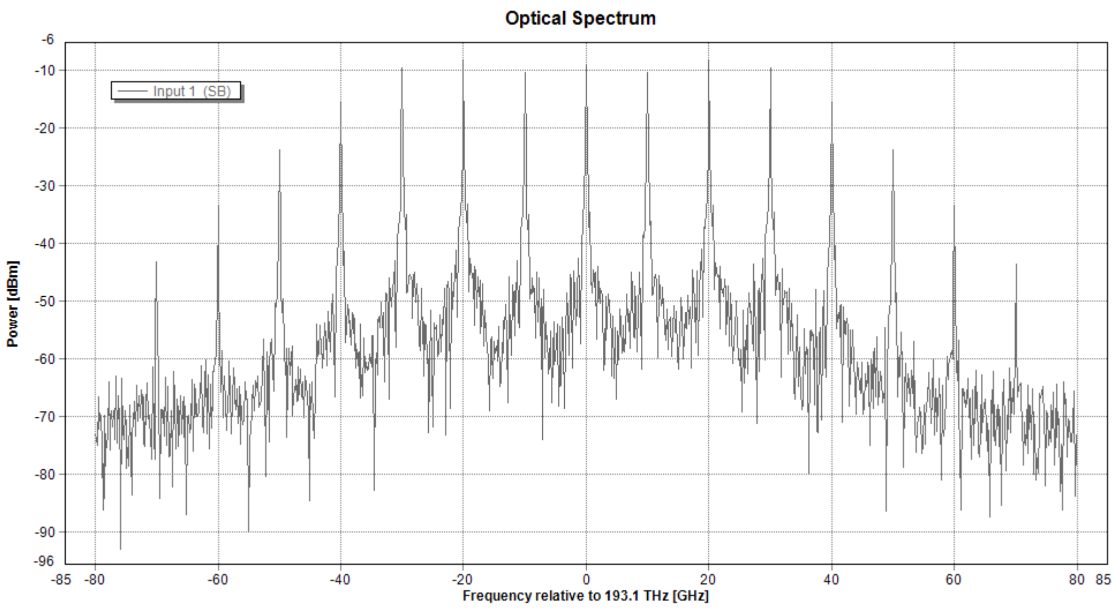

Figure 3.11-Results of the simulation of the DS MOD setup for 10GHz.

➢ 12.5GHz

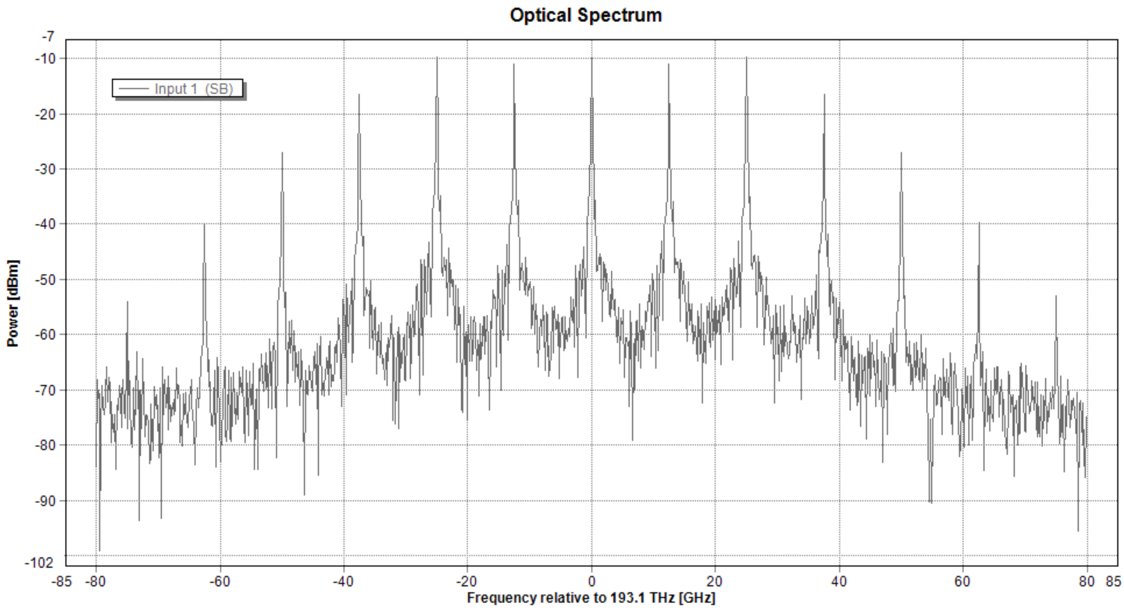

Figure 3.12-Results of the simulation of the DS MOD setup for 12.5GHz.

Analyzing the results obtained by the simulations in the figures 3.8-3.12, it is possible to confirm that similarly to what happened in the previous setup, the spacing between carriers is equivalent to the frequencies set in the signal generator. It is also possible to observe that using the set of tunings presented in the table 3.2 resulted in a flat spectrum with a maximum spectral ripple of 5dB for all the considered frequencies, except for one of the carriers at 3.125GHz. For 3.125GHz 17 carriers were obtained, for 5GHz 11 carriers were obtained, for 6.25GHz 9 carriers were obtained, for 10GHz 7 carriers were obtained and for 12.5GHz 5 carriers were obtained. As the frequency response of the MZM model was ideal, if the gain of the RF signals had remained as high in the simulations for the higher frequencies as it was in the simulation for 3.125GHz, the results would have presented the same number of channels for each frequency, but with different spacing. As this won't happen in a real environment, the values of the RF signal gains were decreased for higher frequencies in order to better replicate what would happen with a MZM with a non-ideal frequency response.

4. Experimental results

4.1. Single stage dual arm driven MZM

4.1.1. Assembly and configuration of the setup

In order to experimentally test the SS MZM as a suitable method for generation of optical multi-carriers, the setup shown on the figure 4.1 was assembled. In this figure it is possible to see all the components used in this experiment. In the bottom level from the left to the right, there are a continuous wave (CW) laser, a polarization controller (PC), a mach-zehnder modulator (MZM) and an optical power meter. In the top level there are a signal generator and an optical complex spectrum analyzer. There are also a power splitter and two phase shifters in the top of the MZM. The process of assembly and configuration of this setup will now be explained:

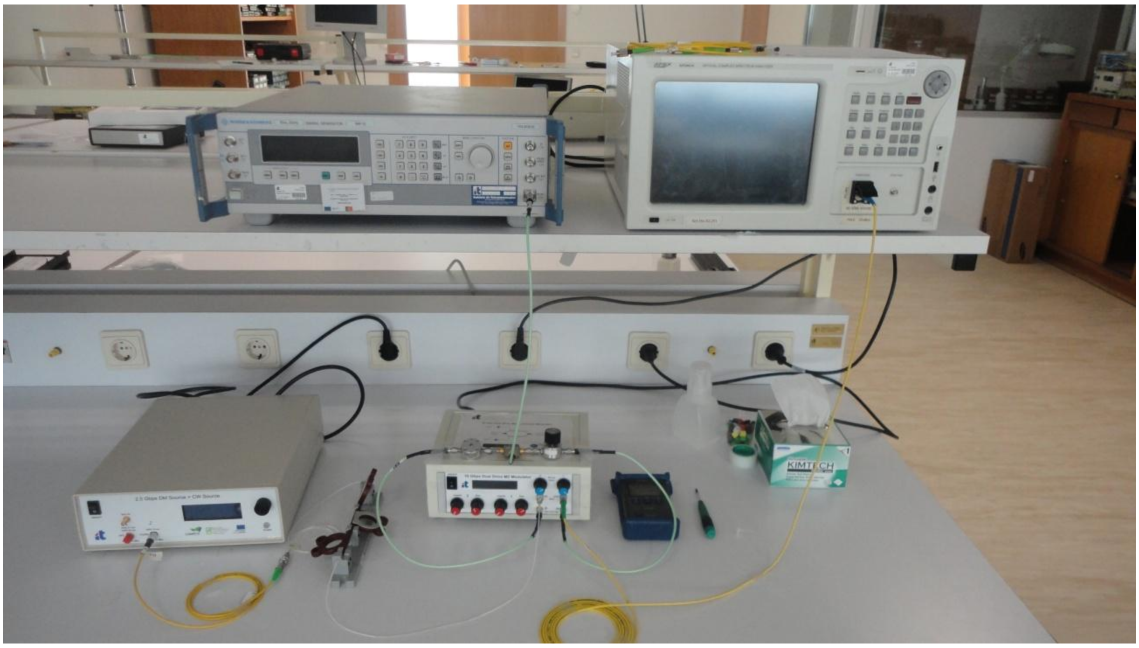

Figure 4.1-Complete comb generator setup based on a single stage dual arm driven MZM.

➢ Assembly of the laser, polarization controller, MZM and OCSA

A fiber cable is connected between one of the outputs of the CW laser and the PC, which will allow modifying the polarization state of the light to guarantee maximum power. The laser output selected was the one transmitted at 1550nm.

The polarization controller is connected to the optical input of the MZM. The output of the MZM is connected to the optical input of the OCSA by a fiber cable. The MZM used has integrated amplifiers for both RF inputs.

➢ Optical components settings

○ The continuous wave laser;

The CW Laser is set with a current that will provide the signal with enough power to be read by the OCSA and that will remain constant during the experiments. This is done by selecting the bias current of the laser output in use and setting the Iset parameter to the desired current, which was 37mA for this experiment. Lastly the laser is enabled to feed the signal into the fiber.

○ Polarization controller;

An optical power meter is connected to the fiber in the output of the PC. When the PC is reading the signal power, the 3 tunable parts of the PC are adjusted one at a time until the maximum power value is achieved. The power meter is then disconnected and the fiber is connected again to the OCSA.

○ Optical complex spectrum analyzer;

After selecting the Spectrum option, the OCSA is set to display the spectrum in wavelength rather than in frequency, the central wavelength is set to 1550nm and the span is set to display the desired window range.

- **Assembly and configuration of the signal generator and phase shifters**

A RF cable is connected to the RF 50Ω output of the signal generator, the other end of the cable is connected to a power splitter. Each output of the power splitter is connected to a different phase shifter. Both phase shifters are then connected to the RF inputs of the MZM via RF cables.

The signal generator is set to values between 3.125GHz and 12.5GHz (UDWDM-PON) and the power of the signal is set to the maximum value of 14.2dBm.

- **Adjusting the MZM and the phase shifters to get the desired comb**

With the whole system running it is possible to see the spectrum of the signal in the OCSA, but in order to achieve the desired flatness and number of channels, the phase shifters as well as the MZM gain control and DC voltages must be carefully adjusted until an optimum point is achieved, with the desired spectral flatness and number of channels.

The values obtained in the chapter 3 of this dissertation were used as a starting point for the experimental part, but in order to accommodate the differences from the models to the real components used (e.g. the used MZM doesn't have an ideal frequency response), further tuning was necessary. The amplifiers[14] were tuned in the terms of gain control bias and not direct gain as in the simulation part. The phase shifters were carefully tuned but the used value wasn't measured due to lack of equipment.

Using the frequency values of 3.125 GHz, 5 GHz, 6.25 GHz, 10 GHz and 12.5 GHz on the signal generator and the set of tunings present in the table 4.1 the following spectra were achieved.

- **MZM tunings:**

Frequency(GHz)	3,125	5	6,25	10	12,5
MZI Vb1(V)	8,55	8,55	8,55	8,49	8,3
MZI Vb2(V)	4,47	4,47	4,47	2,91	2,19
RF Amp Vgc1(V)	-2	-2	-2	0	0
RFAmp Vgc2(V)	0	0	0	-6,3	-7,6

Table 4.1-MZM tunings for the single stage dual arm driven MZM.

4.1.2. **Experimental results**

4.1.2.1. 3.125GHz

Using 3.125 GHz frequency on the signal generator, it is possible to observe in the spectrum shown in the figure 4.2 that 18 carriers within 4.5dB spectral ripple were successfully generated with 3.125GHz (25pm) spacing between them. The maximum power value achieved was -18.5dBm.

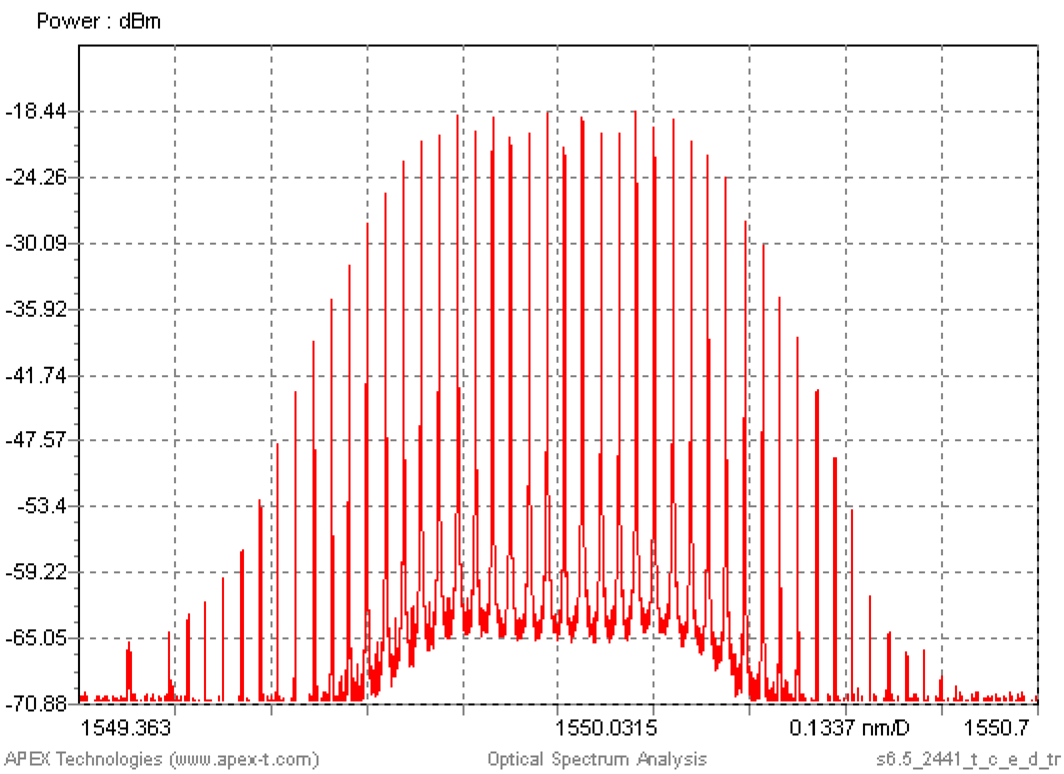

Figure 4.2-Optical frequency comb for the single stage dual arm driven MZM at 3.125GHz.

4.1.2.2. 5GHz

Using 5 GHz frequency on the signal generator, it is possible to observe in the spectrum shown in the figure 4.3 that 12 carriers within 4.5dB spectral ripple were successfully generated with 5GHz (40pm) spacing between them. The maximum power value achieved was -15dBm.

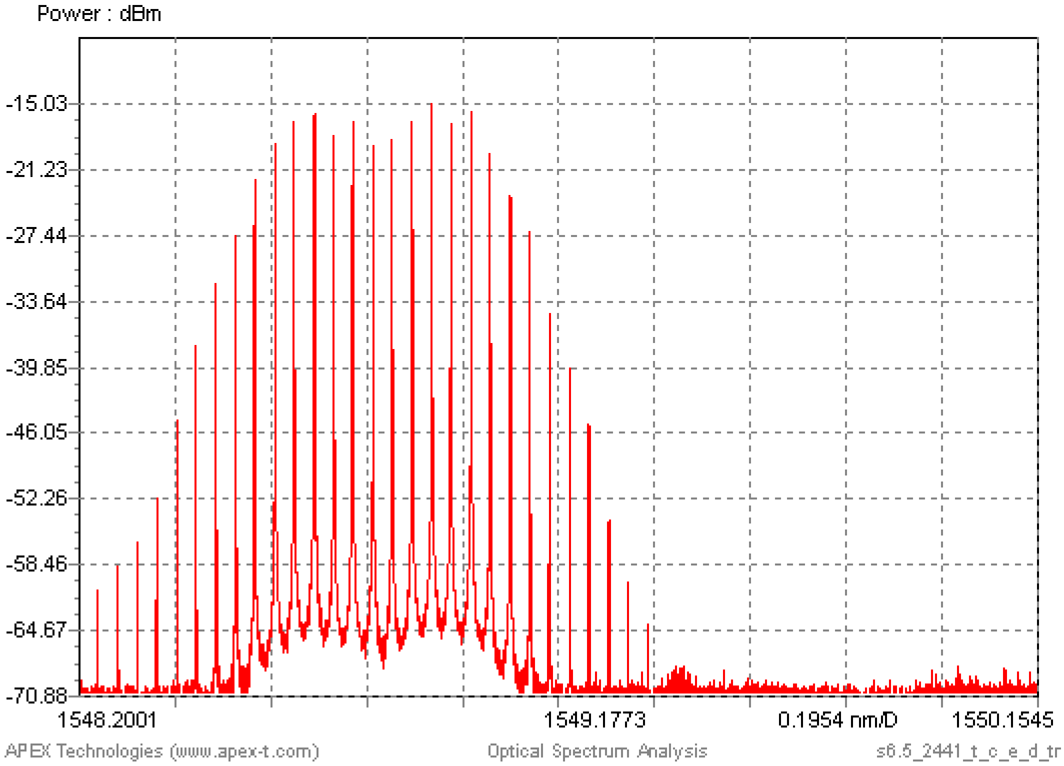

Figure 4.3-Optical frequency comb for the single stage dual arm driven MZM at 5GHz.

4.1.2.3. 6.25GHz

Using 6.25 GHz frequency on the signal generator, it is possible to observe in the spectrum shown in the figure 4.4 that 10 carriers within 4.5dB spectral ripple were successfully generated with 6.25GHz (50pm) spacing between them. The maximum power value achieved was -13.5dBm.

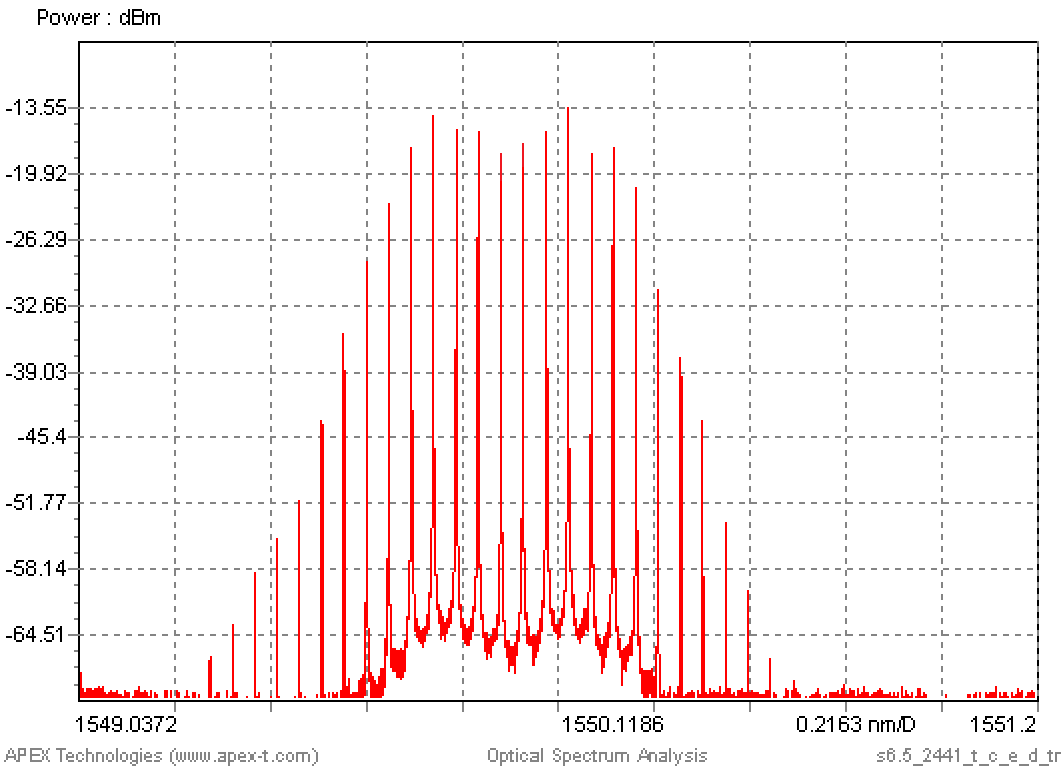

Figure 4.4-Optical frequency comb for the single stage dual arm driven MZM at 6.25GHz.

4.1.2.4. 10GHz

Using 10 GHz frequency on the signal generator, it is possible to observe in the spectrum shown in the figure 4.5 that 7 carriers within 4.5dB spectral ripple were successfully generated with 10GHz (80pm) spacing between them. The maximum power value achieved was -18.5dBm.

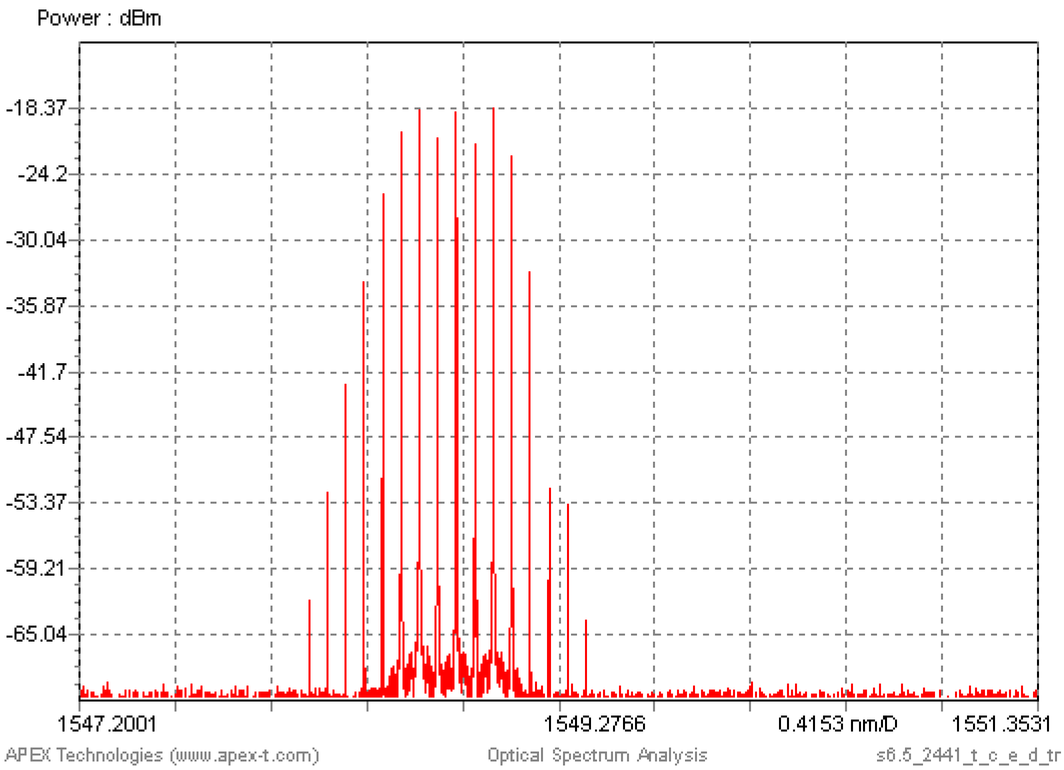

Figure 4.5-Optical frequency comb for the single stage dual arm driven MZM at 10GHz.

4.1.2.5. 12.5GHz

Using 12.5 GHz frequency on the signal generator, it is possible to observe in the spectrum shown in the figure 4.6 that 5 carriers within 3dB spectral ripple were successfully generated with 12.5GHz (100pm) spacing between them. The maximum power value achieved was -10.5dBm.

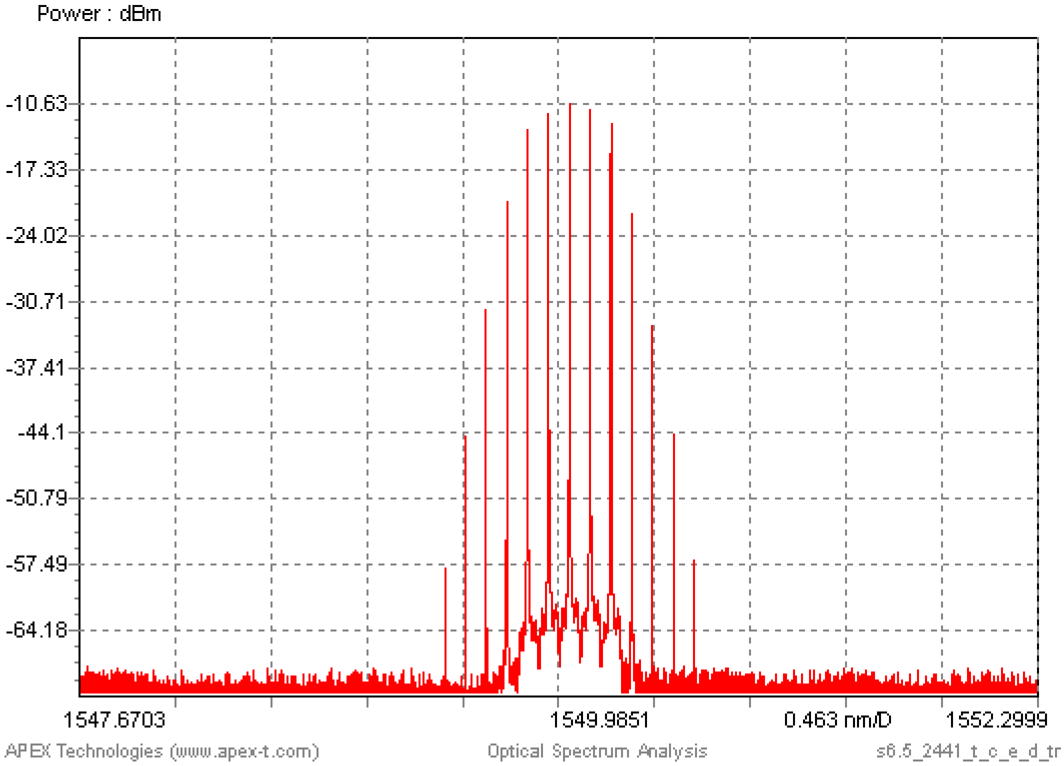

Figure 4.6-Optical frequency comb for the single stage dual arm driven MZM at 12.5GHz.

4.2. Dual stage IM and PM

4.2.1. Assembly and configuration of the setup

In order to experimentally test the DS MOD as a suitable method for generation of optical multi-carriers, the setup shown on the figure 4.7 was assembled. In this figure it is possible to see all the components used in this experiment. In the bottom level, there are a CW laser, two polarization controllers, a MZM and a phase modulator (PM). In the top level there are a signal generator and an OCSA. There are also a power splitter and two phase shifters in the top of the MZM. The process of assembly and configuration of this setup will now be explained:

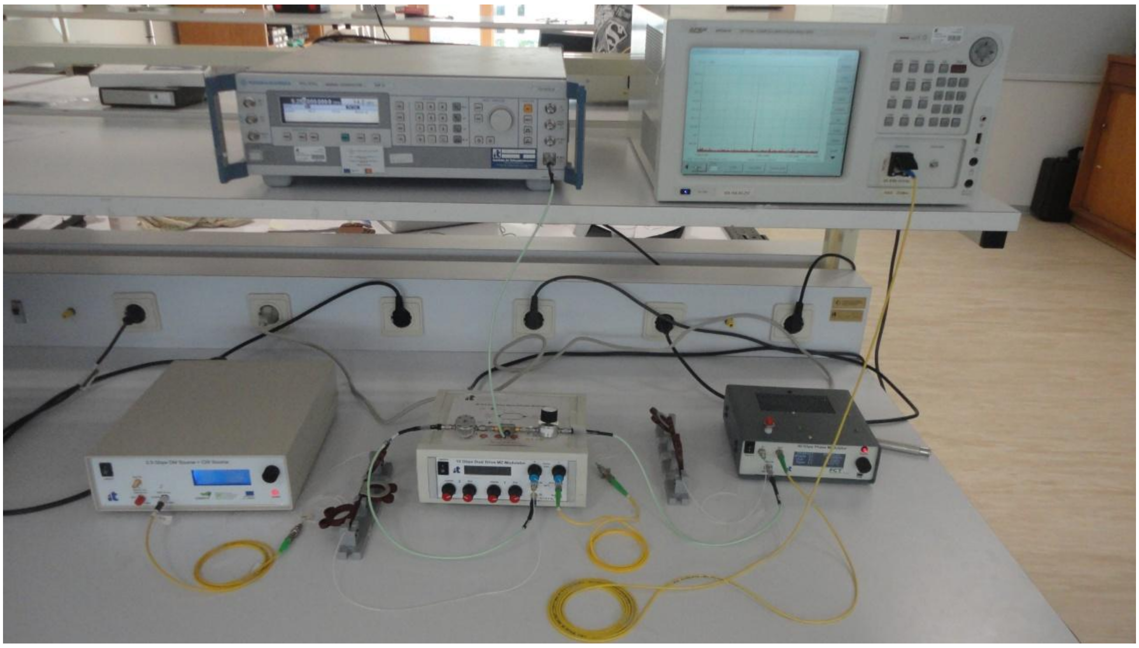

Figure 4.7-Complete comb generator setup based on dual stage IM and PM.

- **Assembly of the laser, polarization controllers, intensity modulator, phase modulator and OCSA**

A fiber cable is connected between one of the outputs of the CW laser and the PC. The laser output chosen was the one transmitted at 1550nm.

The polarization controller is connected to the optical input of the MZM, working as intensity modulator. The output of the MZM is connected by a fiber cable to another polarization controller, which is connected to the phase modulator.

The output of the PM is connected to the optical input of the OCSA by a fiber cable.

Both the MZM used as IM and the PM[15] had integrated amplifiers in their RF inputs.

The configuration of the CW laser, polarization controllers and OCSA is identical to the configuration done for the previous experimentally tested setup, the SS MZM.

- **Assembly and configuration of the signal generator and phase shifters**

A RF cable is connected to the RF 50Ω output of the signal generator, the other end of the cable is connected to a power splitter. Each output of the power splitter is connected to a different phase shifter. One of the phase shifters is connected to one of the RF inputs of the intensity modulator and the other phase shifter is connected the RF input of the phase modulator, both via RF cables.

The signal generator is turned on, the frequency is set to values between 3 and 12.5GHz (UDWDM-PON) and the amplitude level of the signal is set to 14.2dBm.

➢ Adjusting the modulators and the phase shifters to get the desired comb

With the whole system running it is possible to see the spectrum of the signal in the OCSA, but in order to achieve the desired flatness and number of channels, the phase shifters as well as the IM gain control and DC voltages and the PM driver gain control and cross point control voltages must be carefully adjusted until an optimum point is achieved, with the desired spectral flatness and number of channels.

The values obtained in the chapter 3 of this dissertation were used as a starting point for the experimental part, but similarly to what happened in the previous experimentally tested setup, as the models and the real components used have differences, further tuning was necessary.

Using the frequency values of 3.125 GHz, 5 GHz, 6.25 GHz, 10 GHz and 12.5 GHz on the signal generator and the set of tunings shown in the table 4.2 the following spectra were achieved.

➢ MZM tunings:

Frequency(GHz)	3,125	5	6,25	10	12,5
MZI Vb1(V)	8,91	8,93	8,93	8,85	8,85
MZI Vb2(V)	7,16	6,46	6,54	6,76	6,76
RF Amp Vgc1(V)	off	off	off	off	off
RFAmp Vgc2(V)	-1,3	-1,3	-0,7	-5,5	-5,5
PM Vamp(V)	1,6	1,6	1,6	1,6	1,6
PM Vxp(V)	2,2	2,2	2,2	2,2	2,2

Table 4.2-MZM tunings for the dual stage IM and PM.

4.2.2. **Experimental results**

4.2.2.1. 3.125GHz

Using 3.125 GHz frequency on the Signal Generator, it is possible to observe in the spectrum shown in the figure 4.8 that 19 carriers within 4dB spectral ripple were successfully generated with 3.125GHz (25pm) spacing between them. The maximum power value achieved was -32dBm.

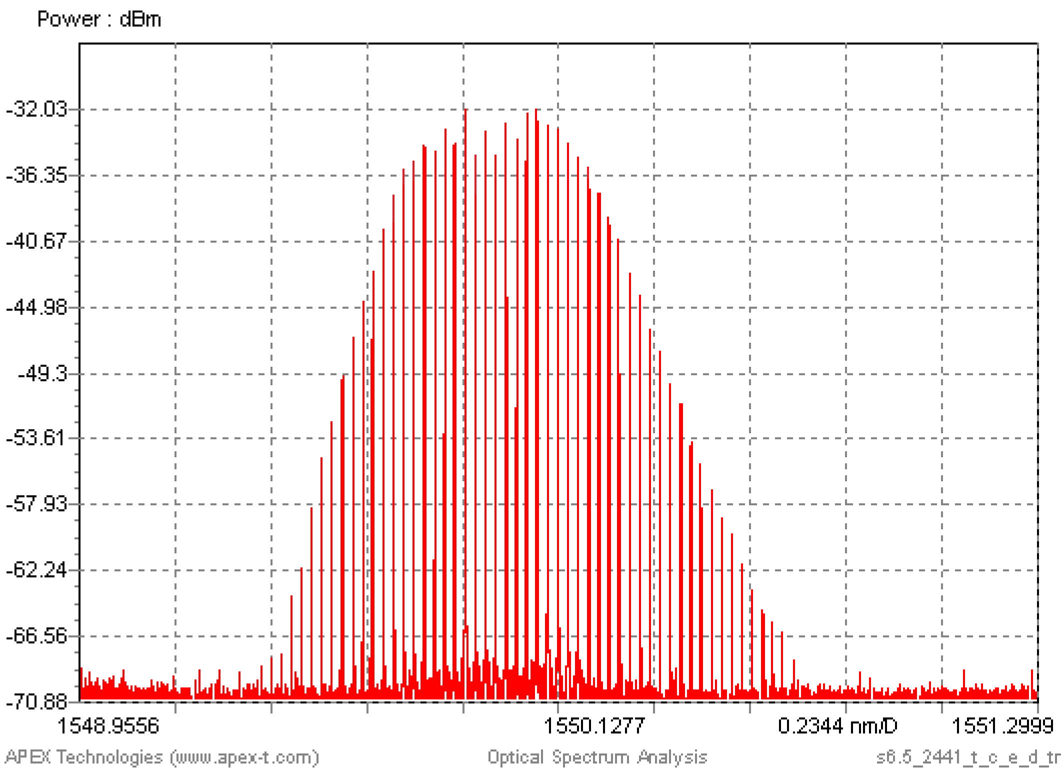

Figure 4.8-Optical frequency comb for the dual stage IM and PM at 3.125GHz.

4.2.2.2. 5GHz

Using 5 GHz frequency on the Signal Generator, it is possible to observe in the spectrum shown in the figure 4.9 that 13 carriers within 3.5dB spectral ripple were successfully generated with 5GHz (40pm) spacing between them. The maximum power value achieved was -28dBm.

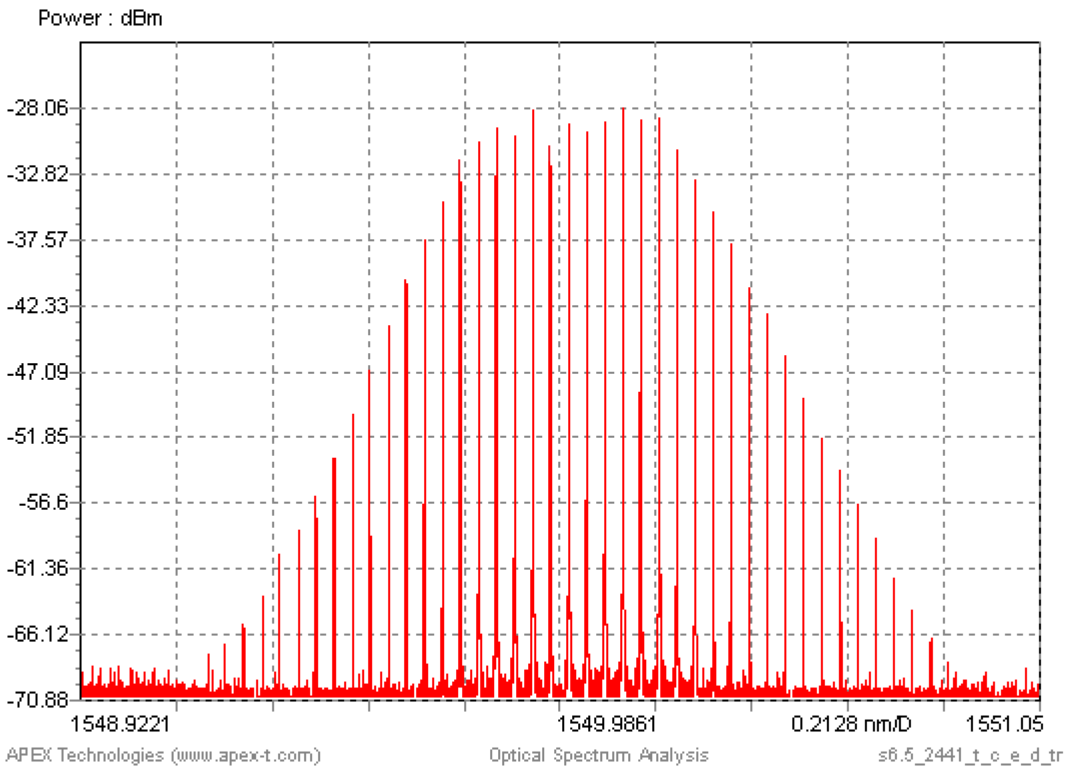

Figure 4.9-Optical frequency comb for the dual stage IM and PM at 5GHz.

4.2.2.3. 6.25GHz

Using 6.25 GHz frequency on the Signal Generator, it is possible to observe in the spectrum shown in the figure 4.10 that 11 carriers within 3.5dB spectral ripple were successfully generated with 6.25GHz (50pm) spacing between them. The maximum power value achieved was -27dBm.

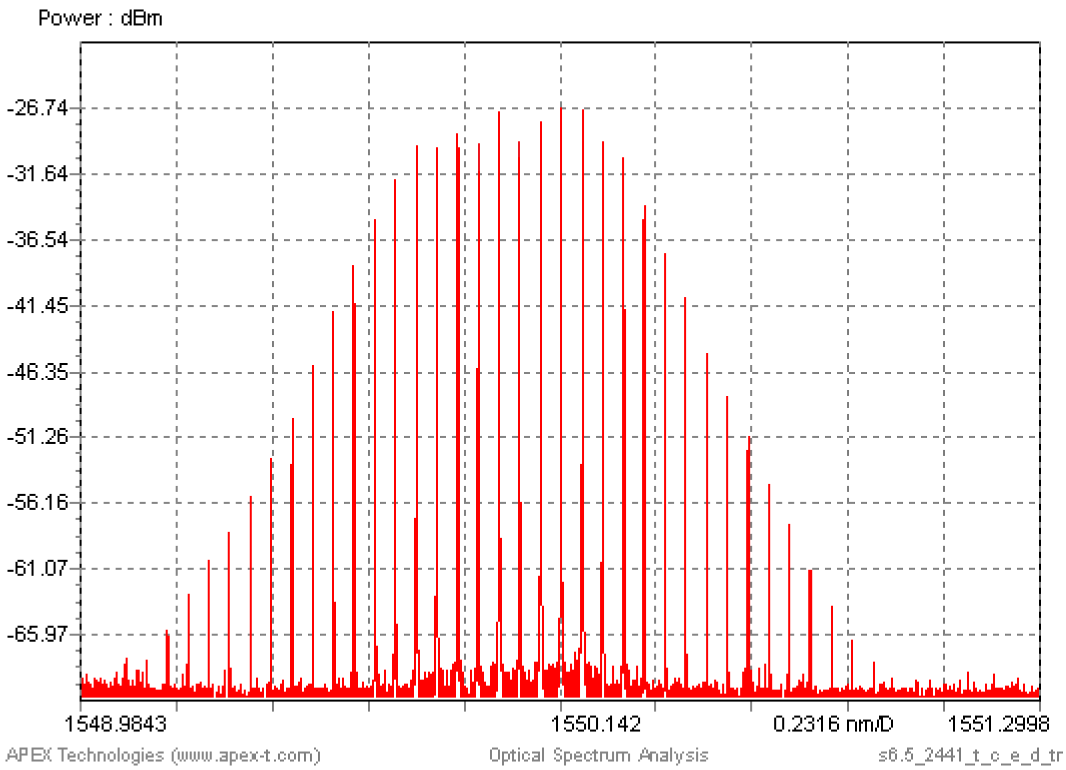

Figure 4.10-Optical frequency comb for the dual stage IM and PM at 6.25GHz.

4.2.2.4. 10GHz

Using 10 GHz frequency on the Signal Generator, it is possible to observe in the spectrum shown in the figure 4.11 that 7 channels within 4dB spectral ripple were successfully generated with 10GHz (80pm) spacing between them. The maximum power value achieved was -23dBm.

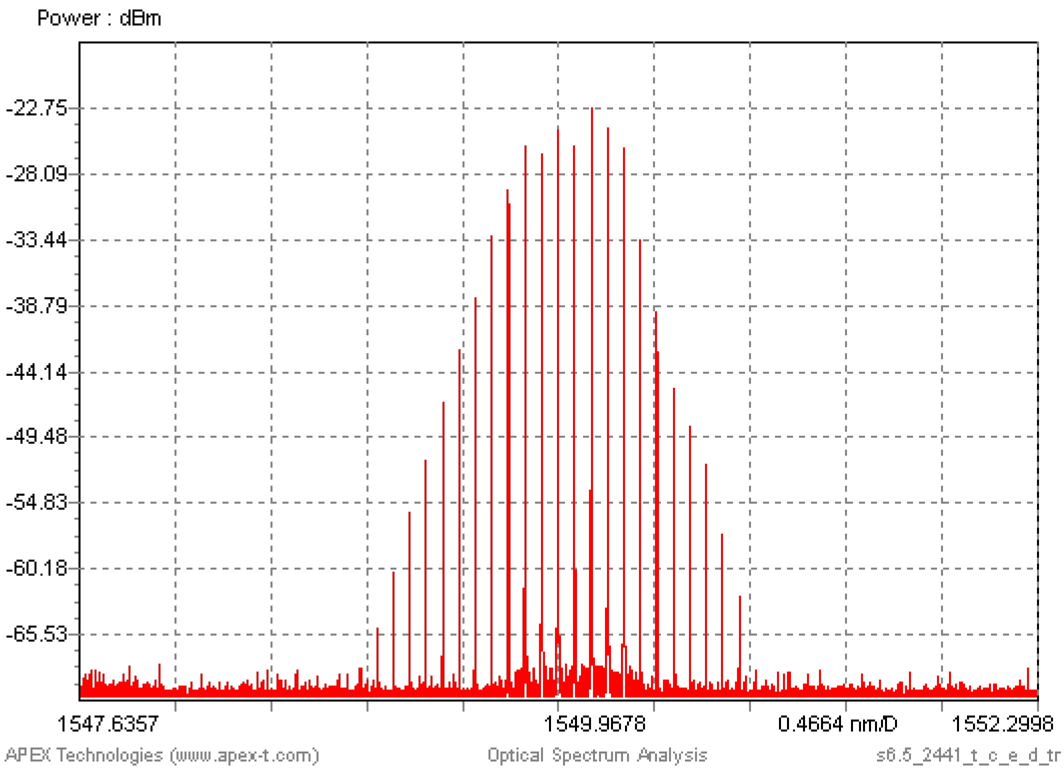

Figure 4.11-Optical frequency comb for the dual stage IM and PM at 10GHz.

4.2.2.5. 12.5GHz

Using 12.5 GHz frequency on the Signal Generator, it is possible to observe in the spectrum shown in the figure 4.12 that 5 carriers within 4dB spectral ripple were successfully generated with 12.5GHz (100pm) spacing between them. The maximum power value achieved was -23dBm.

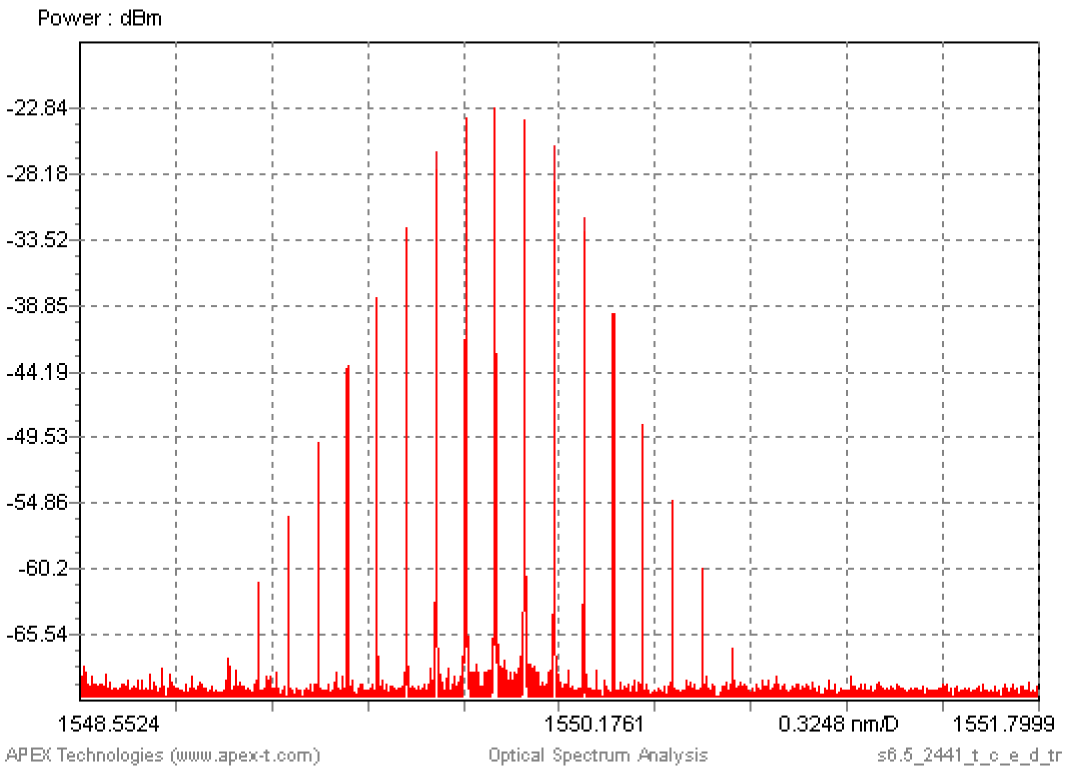

Figure 4.12-Optical frequency comb for the dual stage IM and PM at 12.5GHz.

4.3. Comparison between simulation and experimental results

Comparing simulation and experimental results it is possible to observe that for both setups, the spacing between carriers presents an exact match for all the frequencies tested, which confirms that the spacing between carriers is the same as the frequency set on the RF signal.

It is also possible to observe that as the frequency response of the MZM used experimentally is not ideal, when the spacing between the carriers increases, the number of carriers that will fit in the bandwidth decreases, consequently, for higher frequencies the number of carriers in our comb decreases considerably. This was an expected behavior since there is no MZM with an ideal frequency response in a real environment, but as adjustments were made to the RF signal in the simulations to better replicate the behavior of a MZM with a non-ideal frequency response, the number of carriers obtained in the simulations and in the experimental part are very similar for both setups and for all considered frequencies.

The maximum spectral ripple obtained in the simulation results for the single stage dual arm driven MZM setup was 3dB for all considered frequencies, as for experimental results the maximum spectral ripple found for all the frequencies was 4.5dB, which shows a superior flatness in the simulated combs. For the dual stage IM and PM, the maximum spectral ripple obtained in the simulation results was 5dB and for experimental results the maximum value was 4dB for all considered frequencies, which shows a superior flatness in the combs obtained experimentally. Although there is a slight spectral ripple difference between simulation and experimental results for both setups, this ripple is always inferior to 5dB which can be considered as satisfactory results.

Although the starting point values used for the experimental part came from the values found in the simulations, further optimization was needed to achieve results similar to the ones obtained in the simulation and that are suitable for a multi-carrier comb generator. This happened because the models of the components used in the simulator don't match exactly the real component specifications, e.g. the frequency response of the MZM model was considered ideal.

4.4. Comparison of the experimental results

The results obtained for the two setups may be compared in terms of number of carriers generated, power of the carrier comb and the spacing between carriers.

4.4.1. **Number of carriers generated within 4.5dBm of each other**

Comparing the number of generated carriers between the SS MZM setup and the DS MOD within a 4.5dB spectral ripple for the frequency values of 3.125 GHz, 5 GHz, 6.25 GHz, 10 GHz and 12.5 GHz set in the signal generator, the following numbers of carriers were generated.

Frequency(GHz)	3,125	5	6,25	10	12,5
SS MZM	18	12	10	7	5
DS MOD	19	13	11	7	5

Table 4.3-Number of carriers generated in both setups.

It is possible to see in the table 4.3 that the results between the two setups were very close for all tested frequencies. For 3.125GHz, 5GHz and 6.25GHz, the spectrum generated by the dual modulator setup showed only 1 carrier more than the one generated by a single modulator. For 10GHz and 12.5GHz the spectrum generated by both setups had the same exact number of carriers. The 4.5dB spectral ripple value was used because it was the greatest spectral ripple considered for all frequencies in both setups and it is a reasonable ripple between carriers from a flattened comb.

4.4.2. **Power of generated carriers**

Comparing the maximum power achieved by the carriers in the combs generated by the SS MZM setup and the DS MOD setup for the frequency values of 3.125 GHz, 5 GHz, 6.25 GHz, 10 GHz and 12.5 GHz set in the signal generator, the following values were obtained.

Frequency(GHz)	3,125	5	6,25	10	12,5
SS MZM(dBm)	-18,5	-15	-13,5	-18,5	-10,5
DS MOD (dBm)	-32	-28	-27	-23	-23

Table 4.4Power of generated carriers for both setups.

It is possible to see in the table 4.4 that the maximum power values obtained by the carriers combs generated by the single stage MZM setup were in average 11.4dB higher than the ones generated by the dual stage modulator setup. The average maximum power value for the SS MZM combs were -15.2dBm and the average maximum power value for the DS MOD combs were -26.6dBm. This happens due to the superior amount of components used on the DS MOD setup, since there is an additional PM and a polarization controller in relation to the SS MZM setup, which will cause more loss.

4.4.3. **Spacing between carriers**

Comparing the spacing between carriers generated by the two setups, for all considered frequencies, it is possible to see in the table 4.5 that for both setups the spacing found in all combs is exactly the same as set in the signal generator.

Frequency(GHz)	3,125	5	6,25	10	12,5
SS MZM(GHz)	3,125	5	6,25	10	12,5
DS MZM(GHz)	3,125	5	6,25	10	12,5

Table 4.5-Spacing between carriers for both setups.

5. Conclusions and Future Work

5.1. Conclusions

In this dissertation it was assessed, both by simulation and experimentally that it is possible to generate a multicarrier comb with the adequate spectral characteristics to be used in an UDWDM-PON scenario. Two setups were tested and validated as suitable methods for generation of optical multi-carriers, one of them based on a single stage dual arm driven mach-zehnder modulator and the other based on a dual stage intensity modulator and phase modulator.

With both setups it was possible to generate a flattened spectrum comb with a satisfactory amount of narrow linewidth carriers within a spectral ripple of 4.5dB for one of the setups and 4dB for the other.

The single stage modulator setup had one less carrier for three of the tested frequencies but on the other hand had an average maximum power value 11.4dB greater than the other setup. One of the main reasons for the power value difference between the setups is the use of less optical components on the single stage MZM setup, which will also result that this setup will be cheaper to implement than the other.

According to the results found it is possible to conclude that even with the slightly inferior number of carriers for smaller frequencies, the single stage MZM setup is a more attractive setup due to its higher simplicity and higher power values.

5.2. Future Work

In this dissertation, methods for generation of optical multi-carrier combs for an UDWDM-PON application are studied, but this dissertation doesn't study the transmission of these combs in a real UDWDM-PON scenario, so for future work of this dissertation it is proposed a study about the transmission and reception of the generated combs in a real UDWDM-PON scenario and how different factors like distance of the transmission and number of carriers can affect the transmitted combs in the other end of the transmission.

References

[1] Einar In De Betou, Christian-Alexander Bunge, Henrik Åhlfeldt, and Magnus Olson, “WDM-PON is a key component in next generation access”, Lightwave, Vol 31, No2, Mar. 2014[Online]. Available: http://www.lightwaveonline.com/articles/print/volume-31/issue-2/features/wdm-pon-is-a-key-component-in-next-generation-access.html

[2] William Stallings, "Data and Computer Communications", Pearson Education, Inc, p.247-248, 2007

[3] Jianping Li, Xuan Li, Xiaoguang Zhang, Feng Tian, and Lixia Xi, “Analysis of the stability and optimizing operation of the single-side-band modulator based on recirculating frequency shifter used for the T-bit/s optical communication transmission”, Optics Express 17609, Vol. 18, No. 17, Aug. 2010

[4] “EPON – Ethernet Passive Optical Network”, IEEE 802.3ah, 2004[Online]. Available: http://www.infocellar.com/networks/new-tech/EPON/EPON.htm

[5] M. Fujiwara, J. Kani, H. Suzuki, K. Araya, and M. Teshima, “Flattened optical multicarrier generation of 12.5GHz spaced 256 channels based on sinusoidal amplitude and phase hybrid modulation”, Electronics Letters, Vol. 37, No. 15, pp. 967-968, Jul. 2001

[6] Taiji Sakamoto, Takashi Yamamoto, Kenji Kurokawa and Shigeru Tomita, “O-band DWDM Transmission over 24 km PCF by Using Optical Frequency Comb Based Multi-carrier Source”, Access Network Service Systems Laboratories, NTT Corporation, 2009

[7] Takahide Sakamoto, Tetsuya Kawanishi, and Masayuki Izutsu, “Optimization of Electro-Optic Comb Generation Using Conventional Mach-Zehnder Modulator”, National Institute of Information and Communications technology, Tokyo, 2007

[8] Jianjun Yu, Ze Dong, and Nan Chi, “1.96 Tb/s (21 100 Gb/s) OFDM Optical Signal Generation and Transmission Over 3200-km Fiber”, IEEE Photonic Technology Letters, Vol. 23, No. 15, pp. 1061-1063, Aug. 2011

[9] Yiguang Wang, Nan Chi, Yufeng Shao, Junwen Zhang, and Shumin Zou, “Investigation of Coherent Optical Multi-Carriers Generation Based on Concatenated Phase Modulator and Mach-Zehnder Intensity Modulator”,

Department of Communication Science and Engineering, Fudan University, 2011

[10] Yiran Ma, Qi Yang, Yan Tang, Simin Chen, and William Shieh, “1-Tb/s Single-Channel Coherent Optical OFDM Transmission With Orthogonal-Band Multiplexing and Subwavelength Bandwidth Access”, Journal of Lightwave Technology, Vol. 28, No. 4, pp. 308-315, Feb. 2010

[11] S. Chandrasekhar, Xiang Liu, B. Zhu, and D. W. Peckham, “Transmission of a 1.2-Tb/s 24-Carrier No-Guard-Interval Coherent OFDM Superchannel over 7200-km of Ultra-Large-Area Fiber”, 2010

[12] VPI Photonics. Available: http://www.vpiphotonics.com/

[13] “10Gb/s Dual Drive Mach-Zehnder (DDMZ) Modulator”, JDSU, Mar. 2007

[14] ” MODEL 5865 12.5 GB/S DRIVER AMPLIFIER”, Picosecond Pulse Labs, Dec. 2008

[15] “40 Gbps NRZ / RZ Medium Output Voltage Driver Module”, Photline Technologies, 2010